

FREWARE GIS TOOL FOR THE TECHNO-ECONOMIC EVALUATION OF RURAL ELECTRIFICATION ALTERNATIVES

Mirelys Torres-Pérez¹, Javier Domínguez Bravo², Cesar Hernández Leyva³, Marieta Peña Abreu⁴

¹ ORCID: 0000-0001-7266-420X

² ORCID: 0000-0002-9677-7265

³ ORCID: 0000-0002-3605-6191

⁴ ORCID: 0000-0002-7714-2205

¹ University of Las Tunas

Avenida 30 de Noviembre S/N, Reparto Aurora, 75100, Las Tunas, **Cuba**

² Center for Energy, Environmental and Technological Research (CIEMAT)

Centro de la Moncloa, Complutense, 40, 28040, Madrid, **Spain**

³ Independent researcher, Calle Asturias #2, Aviles, 33404, Asturias, **Spain**

⁴ University of Informatics Sciences

Carretera a San Antonio de los Baños Km 2 ½, Torrens, Boyeros, 19370, La Habana, **Cuba**

ABSTRACT

Energy access is a crucial step for the socio-economic development of isolated communities and for preventing disease and fight pandemics across many parts of the world. In this research, is presented a freeware GIS tool for the techno-economic evaluation of rural electrification alternatives, based on a plugin for the QGIS (Quantum GIS) called LECGIS. The tool carries out an implementation of the IntiGIS model to perform the calculations, a flexible model capable of adapting to the realities of different scenarios. In addition, it allows the clustering of isolated houses, for a better modelling of the cost of the centralized systems. It is described the application of this tool in the Guamá (Cuba) case study and the comparisons of the results with the obtained in Intigis 1.0. It is concluded that the LECGIS plugin allows to calculate and compare seven technological options for the electrification of communities, supporting the decision-making in the planning of rural electrification projects.

Keywords: rural electrification, Levelized Cost of Electricity (LCOE), Renewable Energy Sources (RES), decision supporting tool, Geographic Information Systems (GIS), IntiGIS

INTRODUCTION

Ensure access to affordable, reliable, sustainable and modern energy for all, is still a firm aspiration of the Sustainable Development Goal number 7 (SDG7). Energy services are key to preventing disease and

fight pandemics across many parts of the world [ONU, 2020]. Methods for electrification planning are diverse, and go from the range of “rational” least-cost optimal [Ellman, 2015, Kemausuor et al., 2014, Mentis et al., 2017, Pinedo-Pascua, 2010], to highly participatory approaches [Cherni et al., 2007, González

✉ mtperetz@ult.edu.cu, ✉ javier.dominguez@ciemat.es, ✉ tatico890530@gmail.com, ✉ mpabreu@uci.cu

Morera et al., 2017]. Technocratic methods to rational planning, benefit from their capacity to analyze large scale regions.

Computer based techno-economic models facilitate such scaling, nevertheless, these approaches fall short in their ability to incorporate context-specific considerations such as consumer qualities and preferences, political goals, and institutional inertia. At the other side, participatory approaches are highly context-specific and seek to involve final users in the decision-making process [Practical Action, 2016, Pritchett & Woolcock, 2004].

While this may enable better fine-tuning in comparison with the technocratic approaches; participatory does usually require more time, resources, coordination, and focus on small scaling. Therefore, are less capable to take advantage from technical efficiencies of greater scales.

Consequently, the two paradigms can be perceived more as complimentary than substitutive. For instance, techno-economic models can produce plans quickly and serve as a reference to planners, for answer regulatory and business model questions. Decision makers can subsequently deviate from them, according to local contexts and feedback from beneficiaries. Also, can be used to agile compare different systems designs, without incurring in the costs of physically building infrastructure. This is valuable because environments can be heterogeneous and computational tools, may account for details that are complicated for unassisted human planners [Lee, 2018].

Managing plans using GIS have been demonstrated save time and costs relative to classic master planning. A report by the World Bank's Independent Evaluation Group (IEG) [Independent Evaluation Group, 2016] compares "classic" (also referred to as "traditional") master plans to those aided by dynamic GIS mapping activities. The IEG details comprehensive geospatial planning efforts in Rwanda and Kenya, and states that they "each cost about US \$1 million and took one year to prepare" [Independent Evaluation Group,

2016]. On the other side, "classic electrification master plan studies take two to three years, cost more than \$2 million to prepare, and are based on a static framework that is not readily updated" [Independent Evaluation Group, 2016]. These documents can be quickly rendered out-of-date with changing technologies, policy agendas, economics for electricity access, and progress in electrification. The IEG instead recommends systematic least-cost planning supported by geographic information systems.

Several techno-economic electrification models that consider the spatial component (also referred to as LCEM, Least-Cost Electrification Models) have been proposed [Ellman, 2015, Kemausuor et al., 2014, Mentis et al., 2017, Pinedo-Pascua, 2010]. However, despite of the efforts made, there is not a methodology or model of planning, universally accepted. In this sense, there is a significant variability between the computational logics adopted for the models. The ways in which they fight with the missing data, and the different simplifications that they realize to face up to the computational complexity, that involves determining the ideal position of every technology. In the same way vary: the parameters are used, the technologies that are considered, as well as geographies (regions within countries, countries and continents) in which they are applied [Morrissey, 2019].

The creation of the planning analyses may also be limited, for the costs related to the use and/or acquisition of some models, since in general they are based on privative software. In order to achieve greater diffusion and accessibility, this is an important issue to solve, because some users can't afford this charge due to the limited budget of their projects. In line with the above, this paper describes a freeware GIS tool for the techno-economic evaluation of rural electrification alternatives. It carries out an implementation of the IntiGIS model to perform the calculations, a flexible model capable of adapting to the realities of different scenarios.

RESEARCH BACKGROUND AND METHODOLOGY

In the middle nineties, the European Union decided to fund the research project SOLARGIS¹: Integration of renewable energies for decentralized electricity production in regions of European Economic Community and developing countries [Solargis-Team, 1996]. The SOLARGIS methodology is based on a calculation and comparison of LCOE, pixel by pixel, of the kWh produced by the systems included in the analysis, both renewable and non-renewable. The methodology were applied with satisfactory results in the state of Karnataka in India [Mahmmud et al., 1996], on the island of Santiago (Cabo Verde) [Monteiro et al., 1998] and in several Tunisian cities [Vandenbergh et al., 1999].

This first version was improvement later to SOLARGIS II, in the frame of the collaboration established between the CIEMAT and UPM (Polytechnic University of Madrid). The aim of this collaboration was to determine the grade of uncertainty of the results provided by SOLARGIS and to develop a new application with high certainty in the results quality [Amador, 2000, Amador & Domínguez, 2005]. Special mention needs to be paid to the spatial sensitivity analysis implemented to check the stability of the results [Amador & Domínguez, 2006].

The continuity of the previous study, led into a new model for rural electrification with renewable energies: IntiGIS. This model included new advances in methodological questions as well as the incorporation of new renewable technologies and the application to new areas, specially, to Latin America countries [Domínguez et al., 2008]. Finally, Irene Pinedo in her PhD thesis create the first version of the IntiGIS tool [Pinedo-Pascua, 2010]. For the validation, study

of three cases were carried out: Guamá (Cuba), Acandí (Colombia) and Cobán (Guatemala).

In addition, other cases study have been made: in the province of Carchi in Ecuador [Martínez Sarmiento, 2012], in Sao Tome Island (Africa) [Pons et al., 2013]. Also Alba Page Arias, made a case study for the entire Ghana country [Page Arias, 2015], and also started the work for the upgrade from IntiGIS 1.0 (ArcGIS 9.x) to IntiGIS 2.0 (ArcGIS 10.x). In this sense, a new Guamá case study was developed [Romero Otero, 2016]. All mentioned studies were done using an implementation of the model based on ArcGIS software, using raster data, and with six electrification alternatives.

In 2017, the CIEMAT and ULT (University of Las Tunas, Cuba); sign an agreement frame of cooperation to establish the collaboration between the two institutions. The current investigation, is accomplished in this frame of cooperation, and aims to provide a continuity of the research [Torres-Pérez, 2018, Torres-Pérez et al., 2019] that describes a tool for the planning of rural electrification taking into account criteria of the territorial ordering. In this sense, was set the objective to create a version of the IntiGIS model in a free software environment and also add a new electrification alternative: mini-grid photovoltaic-diesel [Hernández Leyva, 2019]. Also, ULT is a collaborator of the HIBRI2 project², directed for the CIEMAT, and where several institutions from Spain and Cuba work together [CIEMAT, 2020].

Model general process

As can be seen in the Fig. 1, the general process of the plugin LECGIS (acronym of Levelized Electricity Cost Geographic Information System) is based on four steps. The two first steps are related with the model inputs needed for the calculations of the Levelized Cost of Electricity (LCOE). 1) The user must set the data required for calculations. 2) The plugin will calculate

¹ Developed in the frame of the program JOULE II, this project was coordinated by the Centre d'Energétique Armines (France) and involved several European centers related with renewable energies: Conphoebus (Italy), CIEMAT (Spain), CRES (Greece), INESC (Portugal, RAL (Unite Kingdom) and NMRC (Ireland).

² “Integrated control system for energy supply through hybrid systems in isolated communities in Cuba. Phase II (2018/ACDE/000600)”. Financed by Spanish International Cooperation and Development Agency (AECID), through its call for innovation projects 2018.

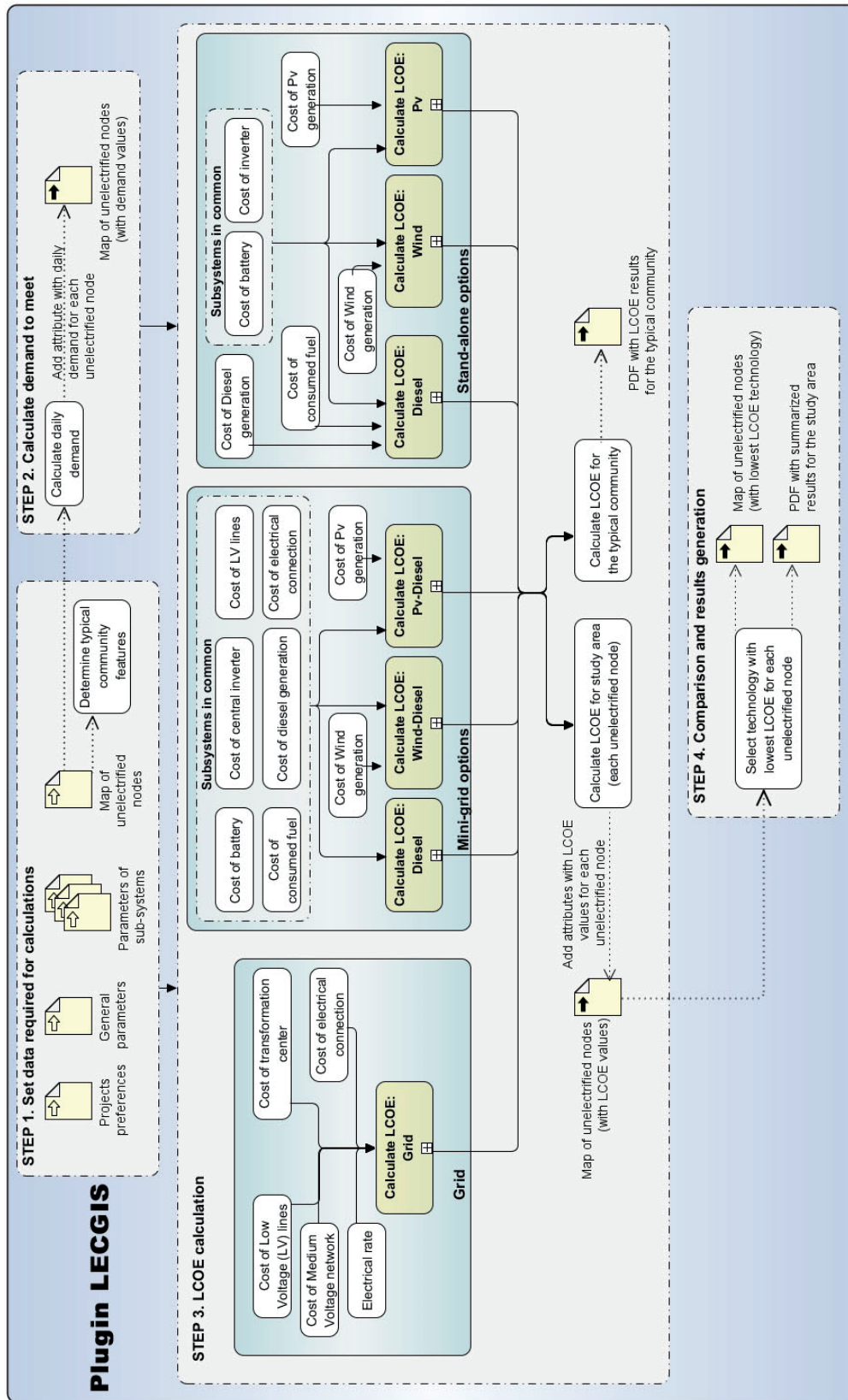


Fig. 1. General process diagram of the plugin LECGIS
Source: own study.

the demand of energy to meet for the electrification alternatives. 3) For each node of the study area will be calculated the LCOE (one or various, depending of the technologies selected by the user). 4) Comparison of rural electrification technologies, to determine the lowest LCOE value for each unelectrified node (this term refers to a register of the map that could represent a house, settlement or community). Additionally, the system will generate PDF reports with the results.

Data requirement

For the use of the plugis is necessary a map in vector format with the geometries that represents the location of the demand nodes. Furthermore, this vector map should have as socioeconomic information associated to the geometries, the attributes: number of houses or people, longitude of low voltage lines, distance to the electrical network, solar radiation and wind speed.

The request of some and other parameters could vary, depending on the electrification alternatives that the user is going to analyze. For example, if the user is not going to analyze an alternative that use wind energy, the wind speed parameter won't be solicited. Figure 2 shows, how to employ the functionalities of the plugin ExamZonas [Torres-Pérez et al., 2019] for gather into a single map, the information needed for the later use of the plugin LECGIS.

Description of the GIS tool

The tool developed is based on QGIS plugin, which is compatible with the versions 2.x. This implement the functionalities: manage projects, calculating data for a house or typical community, calculating demand for houses and communities, calculating LCOE for an area of study, compare systems of electrification and generate PDF reports with LCOE for house or typical community. The main user interface of the plugin (see Fig. 4) is composed for eight tabs: one for the general parameters and the following, for each one of the systems to be considered. At the bottom part there is a progress bar to indicate the advancement of calculations and next to it the icons: save data, editing project, calculate LCOE and compare systems of electrification, in that order from left to right.

For each tab there are two buttons located in the up-right part, for validate data (Fig. 3a) and edit data (Fig. 3b). When the validate button is pressure, the plugin verify the data introduced by the user, and if the data is correct, the button will turn into (Fig. 3c) and the form fields in the tab will disabled.

The user only will be able to edit again the fields, if presses the button edit data, with that the validating button will become red again. Hereafter will describe the data required for calculations and the steps to do in the tool for make the calculations.

First the user must set the project preferences (project name and path), after will appear the main

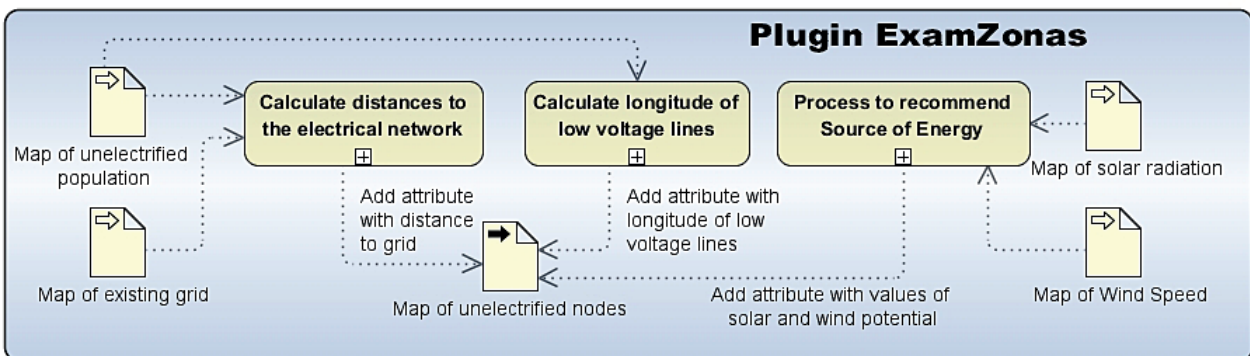


Fig. 2. Functionalities of the plugin ExamZonas to guarantee the data needed for later LCOE calculations
Source: own study.



Fig. 3. Buttons in the GIS tool: a) validate data, b) edit data, c) ready
 Source: own study.

interface of the plugin. On the tab of the general parameters (see Fig. 4), must input the characteristics of the demand scenario and the economic parameters. Also, when loads the map of unelectrified nodes and select the attributes corresponding to each characteristic of the study area, the features of the typical community will be calculated automatically. If the field selected is correct, the result is displayed

next to the right of each field, and the indicator of the field will convert to a green checkbox.

Setting data required for calculations

Furthermore, it is possible to define if the analysis will be done for houses or communities, by marking the checkbox “analysis for houses”. From this way, the tool can distinguish if each node of the map corresponds to a single house or community. In the analysis for houses, the user must select the clustering attribute (identifier of the group who belong each house) for the constructions of mini-grids. Finally, the user must enter the parameters of the rest of the subsystems. On the Fig. 5, can be see the parameters of the Photovoltaic-diesel system.

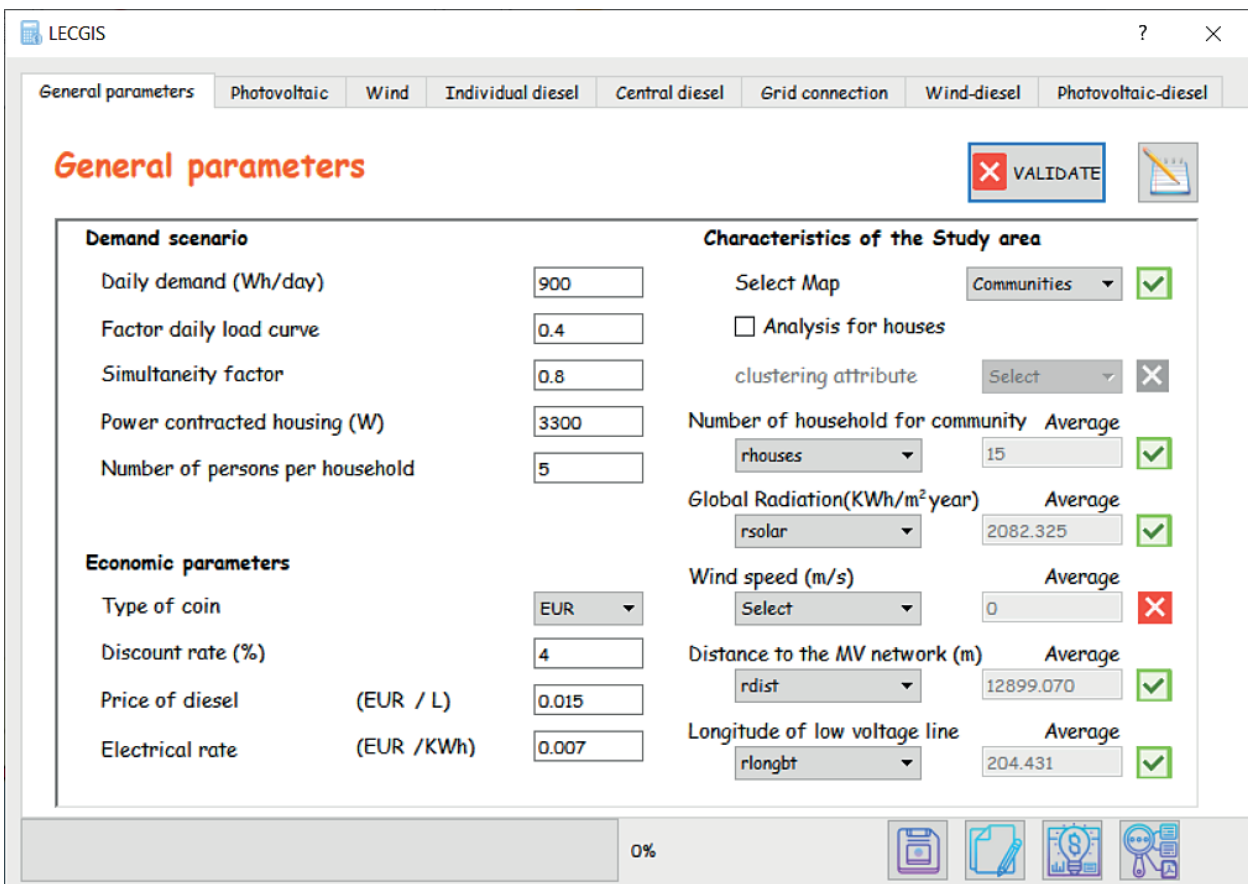


Fig. 4. Tab of the general parameters with data of the Guamá study case
 Source: own study.

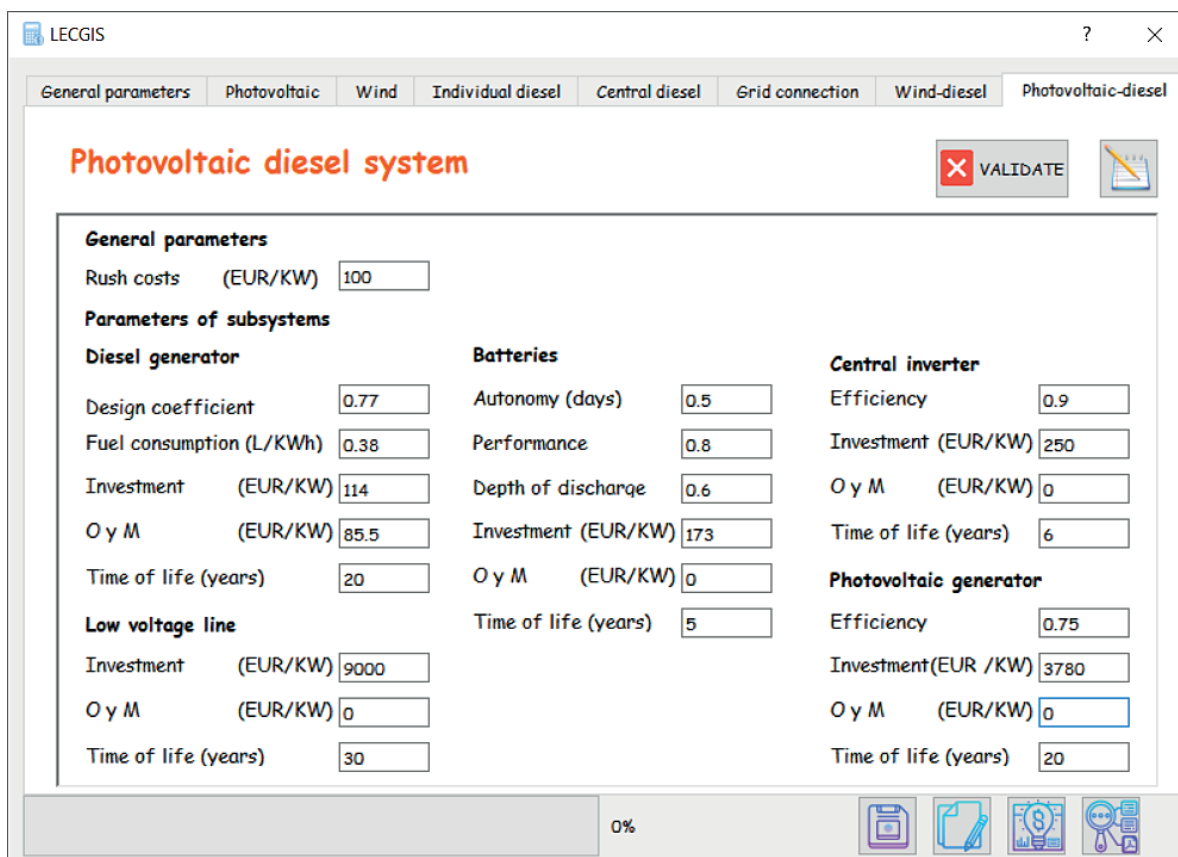


Fig. 5. Fields of the Photovoltaic-diesel system and subsystems
Source: own study.

Calculate demand to meet and LCOE

When the user presses the button for calculate LCOE, will be displayed the interface to select the systems for which the LCOE will be calculated (see Fig. 6). Systems whose data have not been previously validated will appear disabled on the interface, as happen with individual diesel and wind-diesel systems. Also, can select if want to perform the analysis for the study area, typical community or both.

If the user selects the study area analysis, for each node in the map will be calculated the daily demand to meet. The annual demand is a product from the daily demand for 365. Subsequently, for every node of the study area will be calculated the LCOE corresponding to each electrification option. As can be seen in the Fig. 1, the cost of each alternative

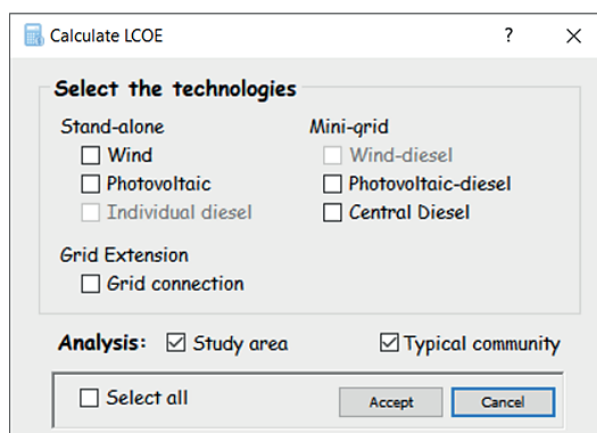


Fig. 6. Interface to select the systems for which the LCOE will be calculated
Source: own study.

of electrification, is a summation of the subsystems that compose it. For more information about the LCOE formulas, consult the thesis [Amador, 2000]. The values of the LCOE will be added to the map, in a new column, when the calculus operations are completed. In the case that be selected a typical community analysis, the system will generate a report in pdf format with the results.

Comparison and result generation

The functionality for compare systems of electrification in a study area, display an interface similar to the Fig. 6, for the selection of the systems to compare. When the accept button is pressed the plugin will select the best alternative of electrification for each node of the study area. Also, a report in pdf format will be created with the results of the comparison of the technologies summarized.

Will be described below, the application of the tool in the municipality of Guamá (Cuba), the maps and parameters (general and for all systems, except photovoltaic-diesel) used was the corresponding to the realized for [Romero Otero, 2016] from a revision of the study case accomplished by [Pinedo-Pascua, 2010] with IntiGIS 1.0. Nevertheless, the distance to the electrical network was calculated using the functionality for calculate distances to the electrical network of the plugin ExamZonas, and employing as inputs the vector layer (points) of the unelectrified communities and the vector layer (lines) of the electrical network, from the study of 2010. As was expected, the obtained distances were different, because in IntiGIS 1.0, the aforementioned vector layers were rasterized to a resolution of 500 m, causing a deviation to the measure of the distances.

The maps of solar radiation, wind speed and longitude of low voltage lines, were converted from raster to vector for their use in LECGIS. Finally, all attributes were gathered into the map of the unelectrified communities. As it was described in previous sections, the parameters (see Fig. 4 and Fig. 5) required for calculations were established, and also were calculated the demand to meet and the LCOE for the seven electrification alternatives.

Another difference was found in the characteristics of the typical community, for illustrate the variation will be taken as example the solar radiation parameter. In this sense, IntiGIS 1.0 calculate de average from all the values existing in the map of solar radiation, but LECGIS calculate the average from the values of the radiation presented in the communities. The Table 1, show the comparison of the values for the Guamá typical community in both tools. In the case of the IntiGIS's wind-diesel system, the cause of the variations was that instead of using 114 €/kWh as the investment for the diesel generator, was used 380 €/kWh (the investment of the individual diesel system). Small variations were got in the others systems, due to the changes in the characteristics of the typical community. All calculations, were verified in the software Mathcad.

Table 1. Comparison of the results obtained in IntiGIS 1.0 and LECGIS tools for the Guamá typical community

Characteristics	IntiGIS 1.0	LECGIS
Number of houses	15	15
Solar radiation (kWh/m ² year)	2065,9	2082.325
Wind speed (m/s)	4.5	4.5
Distance to the MV network (m)	12672,01	12899.07
Longitude of LV line (m)	204,44	204.431
LCOE (cts €/kWh)		
Photovoltaic	62.436	62.255
Wind	80.091	80.091
Individual diesel	282.887	282.887
Central diesel	145.098	145.096
Grid connection	303.906	308.484
Wind-diesel	117.25	81.962
Photovoltaic-diesel	-	166.181

Source: own study.

The results for the study area with the LECGIS tool (see Fig. 7), show a clear prevalence of the photovoltaic system, being the most competitive technology in 58 of the 68 communities. In four communities (number 12, 28, 45 and 62, indicated with red stars in the map), was obtained the photovoltaic system as best alternative, when IntiGIS 1.0 showed the grid connection.

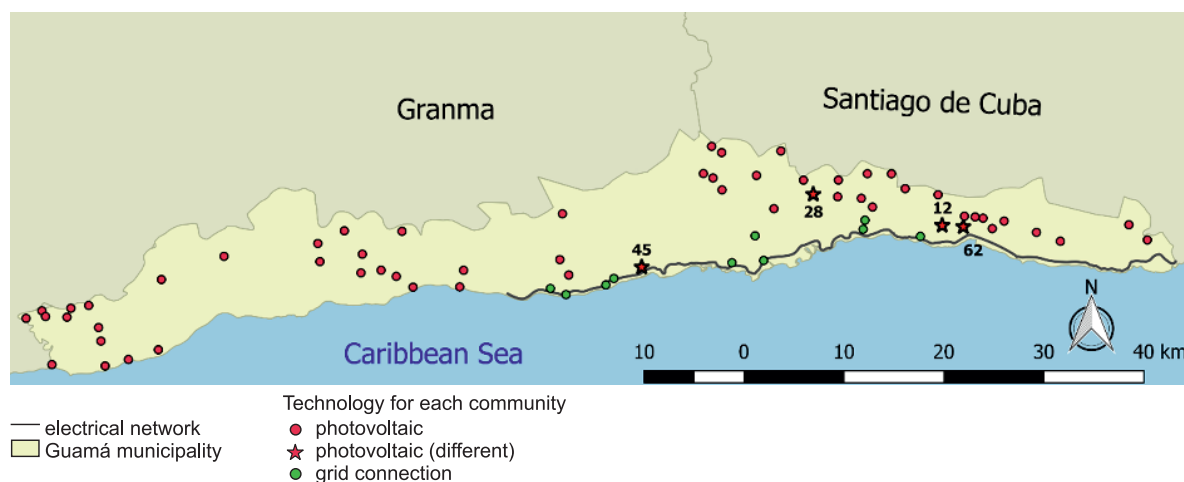


Fig. 7. Most competitive technology for each community of the study area with LECGIS

Source: own study.

Table 2. Comparison of the obtained results with IntiGIS 1.0 and LECGIS tools in the communities' number 12, 28, 45 y 62 of Guamá

Characteristics	12		28		45	62
	IntiGIS 1.0	LECGIS	IntiGIS 1.0	LECGIS	LECGIS	LECGIS
Number of houses	40	40	62	62	4	10
Solar radiation (kWh/m ² year)	2054.95	2054.95	2061.15	2061.15	2149.48	2168.83
Wind speed (m/s)	4.5	4.5	4.5	4.5	4.5	4.5
Distance to the MV network (m)	1500	1634.48	4924.42	4660.14	455.47	971.05
Longitude of LV line (m)	329.20	329.20	198.32	198.32	216.89	157.91
LCOE (cts €/kWh)						
Photovoltaic	62.55	62.55	62.48	62.48	61.54	61.34
Wind	80.09	80.09	80.09	80.09	80.09	80.09
Individual diesel	282.88	282.88	282.88	282.88	282.88	282.88
Central diesel	145.09	164.86	145.09	144.12	147.07	137.72
Grid connection	34.29	74.55	38.32	62.94	110.53	74.99
Wind-diesel	117.25	101.73	117.25	80.99	83.93	74.59
Photovoltaic-diesel	-	186.18	-	130.18	132.18	122.63

Source: own study.

One cause was that IntiGIS 1.0, assigned automatically the grid connection as most competitive option for nodes located less than 800 meters from the electrical network. That is the case of the communities' number 45 and 62³ and the reason why in the Table 2, only appears the LECGIS's values for these communities. Besides, the values of the grid

connection for Intigis 1.0 aren't correct, something that was pointed by [Romero Otero, 2016] on his revision of this study case, with Intigis 1.0, and that we confirmed through the Mathcad. It is notable that the values for this system are lower in IntiGIS 1.0, and that's why it was indicated the grid connection as the best alternative for the communities 12 and 28.

The values for the individual systems (photovoltaic, wind and diesel) are the same in both tools, but the values for the central diesel and wind-diesel,

³ In Intigis 1.0 the distances obtained to the MV network for these communities were 500 m and 707.10 m respectively.

do not match. In addition, the communities 12 and 28 have the same values for the centralized systems in IntiGIS 1.0, even when the characteristics of these communities are distinct. It was confirmed through the Mathcad, that the values that correspond to the centralized systems, are the ones that LECGIS returned.

DISCUSSION, CONCLUSIONS AND NEXT STEPS

The plugin developed in this paper constitutes an effort in the contribution for planning the electrification in developing countries at a national and regional level. The presented approach is complementary to already existing energy planning models, which do not consider the geospatial characteristics of energy resources. In concordance with the aforementioned, the LECGIS plugin allows to calculate and compare the LCOE of a set of seven electrification options: stand-alone (photovoltaic, wind, diesel), mini-grid (diesel, wind-diesel, photovoltaic-diesel) and grid connection, supporting the decision-making in the planning of rural electrification projects. Allows the clustering of isolated houses, for a better modelling of the cost of the centralized systems.

The complementary use of LECGIS with the tool ExamZonas, will improve the electrification strategies towards the implementation of sustainable solutions, with the consideration of criteria and concepts of the territorial ordering, so as to avoid conflicts in land-use or the preservation of resources and the environment. Also, improve the calculation of the longitude of LV lines, considering the geometric center of a group of houses, and no the center of the pixel like the previous versions of IntiGIS based on raster. This have a direct repercussion in the cost of the centralized systems, based on mini-grid.

The development of the tool with freeware facilitates the enlargement of additional components and its employment and diffusion. The tool is currently being further developed, and the improvements will be presented in future publications. Some of the next steps in the progress include: improving the extension

algorithm of the grid and the clustering of households, for deciding whether to serve them with electrification alternatives based on mini-grid or with the grid. Also, may include additional hybrid-technologies combinations.

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