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Dissertation

Design of off-grid renewable energy community electrification projects: analysis of micro-scale resource variations and development of optimization methods

by

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Submitted to the *Departament d'Organització d'Empreses* in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the

Universitat Politècnica de Catalunya

Barcelona, Spain December 2014

Curso académico:

Acta de calificación de tesis doctoral

Nombre y apellidos

Programa de doctorado

Unidad estructural responsable del programa

Resolución del Tribunal

Reunido el Tribunal designado a tal efecto, el doctorando / la doctoranda expone el tema de la su tesis doctoral titulada ____
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“Cuando soplan los vientos del cambio

Algunos construyen murallas,

Otros,

Molinos de viento”

Proverbio chino

Acknowledgements

Quiero agradecer mis directores de tesis, Rafael Pastor, Laia Ferrer y Alberto García por todo el soporte durante el desarrollo de la tesis. Rafa por haber sido una referencia constante a lo largo de estos años. Laia por haberme introducido a un mundo que me sigue sorprendiendo continuamente. Alberto por haber sido mi tutor en temas heurísticos y de programación resolviendo cualquier duda en pocos minutos.

Agradezco Bruno por la siempre completa disponibilidad y por todo el trabajo desarrollado conjuntamente.

Quiero agradecer los profesores y los profesoras del Departament d’Enginyeria Mecànica y del Institut d'Organització i Control de Sistemes Industrials por toda vuestra ayuda durante estos años; Tania por la compañía y el constante buen humor.

I would like to thank people of the ECREEE office in Praia for all the assistance and support provided, Daniel Graça for the information on diesel generator grids in Cape Verde, and Gustavo Herrera for the treatment of topographic maps.

The author is very grateful for all the assistance and support provided by people of the AsoFenix office in Managua. I would like to thank Philipp Blechinger and Jon Leary for the consultancy on the economic study on off-grid electrification projects, Joaquin Mataix, Roberto Clemente and Alexi Funez for the data about wind turbines characteristics and costs.

This thesis was supported by the Spanish Ministry of Education (FPU grant AP2009-0738), the MICINN project ENE2010-15509 and co-financed by the Centre for Development Cooperation of the Universitat Politècnica de Catalunya.

Abstract

Projects relying on renewable energies are a suitable and sustainable option to electrify isolated communities autonomously. These systems produce electricity in a clean and environmentally respectful way and their cost is often lower than national grid extension. Hybrid systems that combine different energy resources (wind and solar) and distribution through microgrids are the most efficient design configurations.

When considering hybrid systems and microgrids, the design of rural electrification projects is referred to as the AVEREMS problem. The optimization of the AVEREMS problem is a complex task that requires the use of specific support tools. In this context, some shortcomings have been encountered in the current state-of-the-art in the design of off-grid electrification projects based on renewable energies, in specific: the lack of knowledge about detailed wind resource studies for this kind of projects and the need of procedures for solving the AVEREMS problem considering generation also far from the demand.

The main objective of this thesis is to tackle these limitations by means of: 1) defining a method for detailed wind resource assessment in rural electrification projects, 2) the development and 3) application of procedures to solve the AVEREMS problem considering micro-scale resource variations and generation in every point of a community (being a demand or a no-demand point).

Firstly, a method for detailed wind resource assessment is presented relying on the use of micro-scale wind flow models: the method is validated in two mountainous communities and applied for the design of a real project in Cape Verde.

Then, different solving procedures are developed: first some indicators are proposed to support algorithms' design, and then two procedures (a deterministic heuristic and a metaheuristic algorithm) are presented in order to solve the AVEREMS problem. Different algorithm versions are analyzed in order to select the ones that give best results. The proposed algorithms, besides considering generation in every point of a certain area (being a demand or a no-demand point), enhance the performance of the currently available tools.

Finally, the design of a real electrification project in Nicaragua is carried out including a micro-scale wind resource assessment and the application of the developed metaheuristic procedure for design optimization.

The wind resource assessment method and the solving procedures developed in this thesis can be easily applied to support the design of off-grid rural electrification projects with renewable energies. Their utilization will improve projects efficiency and sustainability reducing some of the technical issues that still limit their implementation in isolated communities.

Resumen

Los proyectos de electrificación basados en energías renovables han demostrado ser una opción adecuada y sostenible para abastecer comunidades aisladas de forma autónoma. Estos sistemas producen energía de manera limpia y respetuosa del medio ambiente y su coste es a menudo inferior al de extender la red eléctrica nacional. Las configuraciones de diseño más fiables y eficientes utilizan sistemas híbridos que combinan varios recursos (eólico y solar) y distribución mediante microrredes.

El diseño de proyectos de electrificación rural considerando sistemas híbridos y microrredes se ha definido como el problema AVEREMS. La optimización del problema AVEREMS es una tarea compleja que requiere el uso de herramientas de soporte. Actualmente, el proceso de diseño de proyectos de electrificación basados en energía renovables presenta algunas limitaciones. Entre ellas, destacan la falta de conocimientos sobre estudios del recurso eólico y la necesidad de procedimientos para resolver el problema AVEREMS incluyendo la generación alejada de los puntos de consumo para aprovechar las áreas de mayor potencial.

El principal objetivo de esta tesis es abordar dichas limitaciones, mediante: 1) la definición de un método para evaluar en detalle el recurso eólico en proyectos de electrificación rural; 2) el desarrollo y 3) la implementación de procedimientos para resolver el problema AVEREMS considerando la variación del recurso a micro-escala y generación en todos los puntos (sean estos de consumo o de no-consumo) de una determinada área.

Primero se presenta un método para realizar estudios del recurso eólico mediante el uso de modelos de flujo de viento a micro-escala. El método se valida en dos comunidades montañosas y se aplica para el diseño de proyectos reales en Cabo Verde.

Sucesivamente, se desarrollan diferentes procedimientos resolutivos: primero se definen unos indicadores de soporte al diseño, y sucesivamente se presentan dos algoritmos (uno heurístico y otro meta-heurístico) para resolver el problema AVEREMS. Se analizan diferentes versiones de los algoritmos para finalmente seleccionar las que obtienen los mejores resultados. Además de considerar generación en todos los puntos (de consumo o de no-consumo) de una cierta área, los algoritmos propuestos mejoran considerablemente las prestaciones de los métodos disponibles actualmente.

Finalmente, se analiza el diseño de un proyecto de electrificación en una comunidad rural en Nicaragua incluyendo la evaluación de recurso a micro-escala y la aplicación del algoritmo meta-heurístico para la optimización del diseño.

La metodología para la evaluación del recurso eólico y los algoritmos resolutivos desarrollados en esta tesis se pueden fácilmente aplicar para suportar el diseño de proyectos de electrificación rural con energías renovables. Su utilización permitirá mejorar la eficiencia y sostenibilidad de estos proyectos reduciendo algunos de los problemas técnicos que limitan su implementación en comunidades aisladas.

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Figures and Tables

Figures

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Nomenclature

a.g.l.: height above ground level.

Arch: segment of electric cable that connects 2 points of a microgrid.

Branch: set of users (and arches) of a microgrid connected to the generation point passing from the same point. All branches of a microgrid include the generation point (see Figure 2).

Community (or *village*): a group of users. Typical size of a rural community is between 10 and 100 users.

Community scale: a few square kilometers (generally below 20 km^2).

Demand point (or *user*): location of a consumption point, such as a house or a public building, with certain electric energy and power demands. Demand points can also be generation points, i.e. locations where the components for generating and storing energy are installed.

Distribution system: the electric cables that connect the generation system to the users.

Generation point: location where a generation system is installed.

Generation system: group of components installed in a certain point in order to generate and store the electricity. It includes generators (wind turbines and solar panels), controllers, batteries and inverters.

Grid consumption point (or *no-generation point*): a user connected to a microgrid and not being the generation point. They are just consuming energy.

Grid generation point: generation point of a microgrid composed by multiple points.

Hybrid system: a generation system composed by multiple generation technologies based on different resources, such as wind and solar.

Independent generation point (or *independent generation system*): a demand point that is producing energy just for its own consumption.

Microgrid: set of user(s) fed by a generation system placed in a demand or no-demand point. It includes both the generation and the distribution systems.

No-demand point: location that can be a generation point but it is not a demand point.

Off-grid (or *autonomous* or *stand-alone*): not connected to the national electric distribution network.

Preface

This doctoral thesis deals with the design of community off-grid projects based on renewable energies (defined the AVEREMS problem). The main objectives of this thesis are the definition of a method for detailed wind resource assessment in rural electrification projects, the development and the application of procedures to solve the AVEREMS problem considering micro-scale resource variations and generation in every point of a community (even those that are far from the users).

The thesis is presented in the form of a compendium of articles, which is taken under the doctorate studies regulations of the Universitat Politecnica de Catalunya (UPC). The aim of this document is to make a summary of the work done in order to facilitate the reading. The reader can find more details in the Annexes, where the complete articles are reported.

The work is organized as follows. Sections 1, 2, 3 and 4 refer to the introduction, the objective of the thesis, the description of the problem and the state-of-the-art. Sections 5, 6 and 7 are the core of the work done during the thesis and the summary of the 6 papers that constitute the compendium. The paper(s) on which the Section content is based are stated at the beginning of each of these Sections. In Section 5 a procedure for wind resource assessment in rural off-grid electrification projects in mountainous areas is validated and applied for the design of a project in Cape Verde. In Section 6 the procedures developed to solve the AVEREMS problem are described and their performance analyzed. Section 7 deals with the application of the best-performance procedure to design a real project in the central highlands of Nicaragua. Finally, Section 8 presents the conclusions of the thesis indicating some possible future works. The 6 articles that form the compendium are annexed in the Annexes: in Annex A1 there are the 4 articles that have published in journals included in the JCR index; in Annex A2 the 2 articles submitted to journals included in the JCR index that are in process of review.

This thesis has been developed in the department of Mechanical Engineering and the Institute of Industrial and Control Engineering of the UPC. During the 4 years of development of the thesis (started in January 2011), the following stays have been realized: ECREEE in Cape Verde (September 2011) and AsoFenix in Nicaragua (August-September 2012). Furthermore, the research advances were presented in 6 international conferences in Germany (1 conference), Greece (1 conference), Italy (1 conference), Peru (2 conferences) and Spain (1 conference).

1. Introduction

At present, over 1.3 billion people lack access to electricity (International Energy Agency, 2013) particularly affecting rural areas in developing countries (Kanagawa and Nakata, 2008). Generally, the common policy for increasing access to electricity in rural areas is by extending the national grid. However, due to complicated geographical conditions, the widespread presence of isolated villages and the houses' dispersion within them, the expansion of the national grid could sometimes be unfeasible or too expensive (Alliance for Rural Electrification, 2011). Under these circumstances, standalone electrification systems (off-grid generation) are a suitable option for providing electricity to many rural communities (Balamurugan et al., 2009).

In many countries, the conventional strategy for providing electricity to remote areas is by means of installing diesel generators (Raimundo et al., 2010; Marandin et al., 2013). However, diesel generators have some clear disadvantages and limitations, such as the high and variable fuel cost, the continuous requirement of fuel transportation to the community and the inherent carbon dioxide and other pollutants emission.

In this context, off-grid (autonomous) generation options that exploit local renewable energy resources such as hydro, solar and wind energy can be used (Zhou et al., 2010). Projects relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously (Chaurey et al., 2004; Paleta et al., 2012). These systems produce electricity in a clean and environmentally respectful way and their cost is often lower than national grid extension (Chaurey et al., 2004). Furthermore, using locally available resources, they are not dependent from external resources, therefore increasing the long-term sustainability of the projects (Baños et al., 2011; Paleta et al., 2012). In this sense, hydro and photovoltaic systems have been widely used in the last decades in order to cover basic household's needs (Coello et al., 2006) and wind systems are receiving increasing attention (Fang et al., 2012). Hydraulic energy is generally the most convenient technology in sites with adequate hydraulic characteristics (Coello et al., 2006). However if a river with a sufficient flow is not present in the area, this technology must be discarded. Thus this thesis will focus on solar and wind energies.

The design of a community off-grid electrification project based on wind and solar energies should result from a balance between the available energy resources and the energy/power requirements of the users (i.e. demand points such as houses or public buildings). Most isolated rural communities of developing countries are characterized by dispersed house distribution in areas of few squared kilometers and spatially variable energy resources. In particular, wind resource is the most irregular in its distribution and important resource differences have been encountered within the same community in mountainous context (Ferrer-Martí et al., 2009). In these situations, a detailed and reliable micro-scale wind resource assessment is required for the correct design of the system

(Alliance for Rural Electrification, 2011). However, there is still a lack of wind resource assessment procedures validated for off-grid electrification projects.

When dealing with off-grid projects based on renewable energies, hybrid systems that combine different resources and microgrids, where the energy is produced in a certain point and distributed through an electric grid to other consumption points, proved to be most reliable design configurations (Yang et al., 2008; Kirubi et al., 2009). Firstly, a system using a combination of different renewable sources has the advantage of balance and stability that offers the strengths of each type of sources that complement each other (Yang et al., 2008). In particular, hybrid solar/wind systems are one of the most promising generation options (Nandi and Ghosh, 2010). Secondly, microgrids could lead to an important decrease in the final cost of energy in comparison with independent generators, i.e. a demand point that generates energy just for its own consumption, and enhance the flexibility of the system (Kirubi et al., 2009; Quiggin et al., 2012). In fact, areas of high resource could be exploited by microgrids' utilization taking advantage of the economy of scale: more powerful generators are installed in sites with better resource. In scattered communities with isolated users, the combination of independent generators and microgrids is generally the cheapest design solution (Ferrer-Martí et al., 2011).

The design of an electrification project based on renewable energies considering hybrid systems and the combination of independent generation points and microgrids will be referred to as the Autonomous Village Electrification through Renewable Energy and Microgrid Systems (AVEREMS) design problem. The complexity of solving the AVEREMS problem is relevant and is facing several technical issues. The selection of grid generation points and the definition of which points should be connected to a certain microgrid are complex tasks, especially when the resources (e.g. the wind) are highly disperse (Ferrer-Martí et al., 2011). A typical community configuration in mountainous context has houses located in the valley whereas best wind resource is at the hill/mountain-top: the selection of the adequate system configuration (e.g. location of the generation points, definition of the required generators and users to connect) should result from a balance between resource potential differences, the houses distribution and the distance from the high resource area. Furthermore, when multiple renewable energies are considered, the identification of the most adequate combination of generation technologies is not straightforward.

In order to deal with the high design complexity, many tools have been developed in recent years to support the design of hybrid systems (Zhou et al., 2010; Baños et al., 2011; Luna-Rubio et al., 2012) and several software are available, such as HOGA, HOMER and HYBRID2 (International Energy Agency, 2011; Sinha and Chandel, 2014). These tools are currently applied for the design of different projects all around the world (Himri et al., 2008; Lal and Raturi, 2012; Aagreh and Al-Ghzawi, 2013). However, most of them define the best combination of energy resources in one point (i.e. design of hybrid systems) but without designing the distribution systems of the microgrids and without taking into account resource spatial variations (Bernal-Agustín and Dufo-López, 2009a; Zhou et al., 2010; Baños et al., 2011).

Currently only two tools (Lambert and Hittle, 2000; Ferrer-Martí et al., 2013) are available that deal, even if with some limitations, with the AVEREMS problem. However both tools have some shortcomings. The method proposed by Lambert and Hittle (2000) limits the number of possible grid generation points and the maximum number of grids in the solution, does not consider electrical distribution constraints and assumes a uniform resource in the area for independent generation points. The method proposed by Ferrer-Martí et al. (2013) assumes that generation points must be located close to the users, while best resource areas could be located far from them, and, due to its high computational requirements, its application may be unreliable when the size of the analyzed community (e.g. the number of demand points) increases.

Finally, it should be noted that promoters of rural electrification projects generally dispose of low resources for project design, making it preferable to use simple and fast tools in order to support the design (Garfì et al., 2011). At the same time, different project configurations should be preferably evaluated for correct planning (Domenech, 2013). In this context, heuristic methods (or simply "heuristics") are a technique commonly used in combinatorial optimization problems (Silver, 2004) in order to accelerate the solving procedure or to make viable the solution to problems that cannot be optimally solved in a practical computational time. Heuristics will generally not guarantee the optimal solution but, when well designed, the obtained solutions can be expected to be fairly close (or even equal) to the optimum value (Gendreau and Potvin, 2005). Thus, heuristic methods are probably the most appropriate technique to apply when dealing with the design optimization of off-grid electrification projects considering hybrid systems and microgrids.

Resuming, the following shortcomings have been encountered in the context of the design of off-grid electrification projects based on renewable energies:

- Lack of a validated procedure for detailed wind resource assessment for this kind of projects.
- Current tools to support the design are mainly focused on hybrid systems, disregarding the definition of generators locations and the distribution system.
- The only tools dealing with the design of off-grid electrification systems taking into account both hybrid systems and microgrids (AVEREMS problem) have some shortcomings that still limit their range of application, such as forcing generation points to be close to the users.
- Lack of methods for solving the AVEREMS problem considering generation in all points of community area (also far from demand points) with low computational requirements.

The main objective of this thesis is to tackle these limitations by means of: 1) defining a procedure for detailed wind resource assessment in rural electrification projects and 2) the development and 3) application of procedures to solve the AVEREMS problem considering micro-scale resource variations and generation in every point of a community. The developed procedures aim to support the design of off-grid rural electrification projects with renewable energies and thus improve their efficiency and sustainability reducing some of the technical issues that still limit their implementation in isolated communities.

The structure of the thesis is reported in the following. First the specific objectives of the thesis are defined (Section 2) and the AVEREMS problem is presented (Section 3). Then the state-of-the-art in wind resource assessment for off-grid electrification problems and in procedures to solve renewable energies design problems is reviewed (Section 4). In Section 5 a procedure for wind resource assessment in rural off-grid electrification projects in mountainous areas is validated and applied for the design of a project in Cape Verde. In Section 6 the proposed procedures to solve the AVEREMS problem are described and their performance analyzed: first some indicators to support the design of off-grid community electrification projects are presented, then these indicators are used to define a greedy deterministic heuristic, and finally, relying on an improved version of the deterministic heuristic, a metaheuristic algorithm based on the greedy randomized adaptive search procedure (GRASP) is described. Section 7 deals with the application of the best developed procedure to design a real project in the central highlands of Nicaragua. Finally, the conclusions of the thesis are reported in Section 8 also indicating some possible future works.

2. Objectives

The aim of this thesis is the development and application of procedures to improve the design of community off-grid electrification projects based on multiple renewable energies considering micro-scale resource variations and a combination of independent generation points and microgrids. For this aim, three main objectives and different specific objectives are defined:

Objective 1. Definition of a procedure for micro-scale wind resource assessment for rural electrification projects.

- 1.1 Analysis of existing methods for detailed wind resource assessment.
- 1.2 Definition and validation of a procedure for micro-scale wind resource mapping in rural off-grid electrification projects in mountainous areas.
- 1.3 Application of the procedure in a case study.

Objective 2. Development of efficient procedures to solve the AVEREMS design problem.

- 2.1 Proposal of indicators in order to select most promising generation points and to support the design of heuristic solving algorithms.
- 2.2 Development of a deterministic heuristic to solve the AVEREMS problem considering generation in every point of a certain area.
- 2.3 Development of a metaheuristic procedure (GRASP) based on the deterministic heuristic, aiming to enhance the solution obtained when a higher computational time is available.
- 2.4 Analysis of the performance of the developed solving procedures and selection of the most appropriate depending on community characteristics and available design resources.

Objective 3. Analysis of the design of a real electrification project including micro-scale wind resource assessment and the application of the developed optimization procedure.

3. Autonomous Village Electrification through Renewable Energy and Microgrid Systems

In this Section the main renewable energy technologies for off-grid generation and the components of an autonomous electrification system are introduced (Section 3.1) and then the AVEREMS (Autonomous Village Electrification through Renewable Energy and Microgrid Systems) problem is presented (Section 3.2).

3.1 Off-grid electrification systems based on renewable energy

The most utilized renewable energy technologies in off-grid electrification systems are hydraulic, solar and wind energy (Alliance for Rural Electrification, 2011). As hydraulic energy is very site dependent and is generally be the preferred technology when available, in this thesis we will focus on wind and solar energies. Main characteristics of these technologies are hereby reported:

- Solar energy: photovoltaic (PV) panels utilize semiconductor-based materials (solar cells) which directly convert solar energy into electricity. This technology is suitable for almost any location around the world and is also relatively easy to install, maintain and scale up. However, initial investment costs are still higher than those of other technologies. Some cost decreases are expected in the future due to technology enhancements.
- Wind energy: small wind turbines (up to 100 kW nominal power) transform the kinetic energy of the wind into mechanical energy, by means of air blades, and then into electric energy, by mean of a stator and a rotor. Due to the multiple moving components it could have high maintenance costs. This technology is very site specific, since wind conditions vary dramatically from place to place, and therefore the wind resource must be carefully studied before a system is installed. In areas with good resource its cost per produced unit of energy could be lower than solar energy. Further enhancements of the technology are expected in the short future.

The combination of multiple technologies (hybrid systems) permits taking advantage of the complementarities of different resources, thus obtaining more reliable systems that are less affected by the fluctuations of a single resource (Yang et al., 2008; Elma and Selamogullari, 2012). In particular, the combination of wind and solar photovoltaic (PV) energies is one of the most successfully implemented configurations (Nema et al., 2009; Nandi and Ghosh, 2010). A stand-alone system based on wind and PV energies always requires a back-up unit, such as batteries, in order to deal with the mismatch between the generation and the demand (Erdinc and Uzunoglu, 2012).

Independent generation systems, i.e. every demand point generates just for its own consumption, are the common choice when electrifying isolated communities with renewable energies (Lemaire, 2011; Leary et al., 2012). On the other hand, a design configuration that showed to be highly effective is the implementation of microgrids that connect various demand points to a single generation system. This configuration could lead to a significant decrease in the final cost of the system in comparison with independent generation systems, enhance the flexibility of the system and improve equity between user consumptions (Kirubi et al., 2009; Alliance for Rural Electrification, 2011). The combination of independent generators and multiple points' microgrids could be the cheapest design solution depending on users' distribution within a community (Ferrer-Martí et al., 2011).

The scheme of a hybrid (wind – solar) off-grid system considering storage in batteries and distribution through a low voltage network is shown in Figure 1. The main components of this system are the following:

1) Generators: produce energy in alternating (wind turbines) or direct (solar panels) current.
2) Controllers: convert to direct current (DC) and control the charge/discharge of the batteries.
3) Batteries: store the energy produced by the generators, receive and supply electricity at DC.
4) Inverters: convert direct to alternating current (AC) at the nominal voltage.
5) Electric cables: configure the microgrid that distributes the energy (low voltage single-phase AC distribution is considered).
6) Electric meters: measure the energy consumed at the demand points.
7) Users (or Demand points): consume the energy.

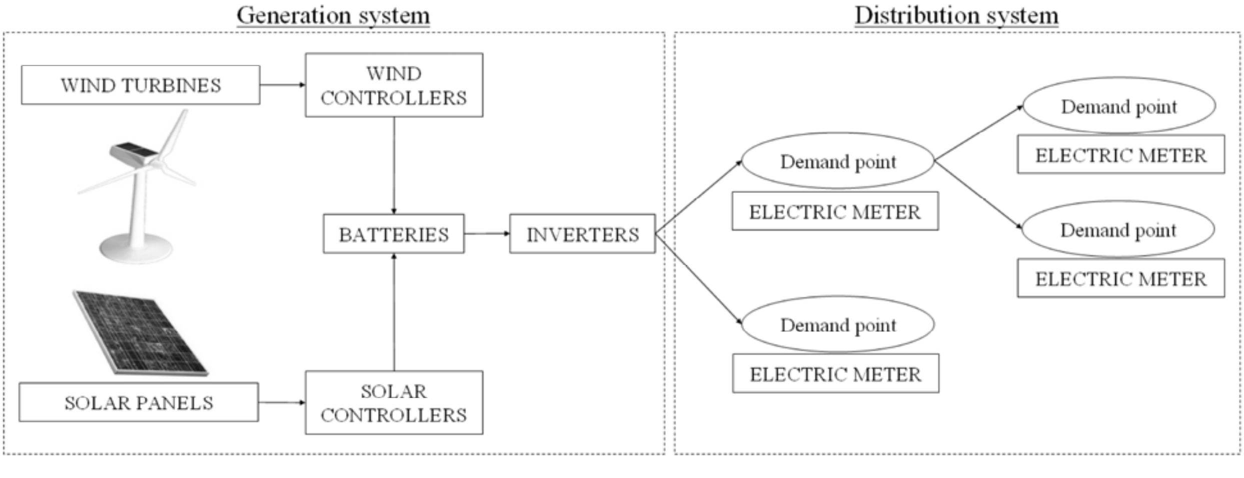

Figure 1 - Scheme of the components involved in a hybrid wind-photovoltaic electrification system (adapted from Ferrer-Martí et al. (2013))

A generation system (or generation point) is composed by the generators (wind turbines and/or solar panels), controllers, batteries and inverters. The energy produced by a generation system is distributed to the users via electric cables that connect the different users (distribution system). The ensemble of the generation system and the distribution system is a "microgrid". If there is a single demand point connected to the generation system located in the same point it is called an "independent generation point". The radial grid configuration (i.e. a single generation point and distribution in form of a tree as in Figure 1) is generally the preferred one in rural electrification projects (Lambert and Hittle, 2000; Alzola et al., 2009). The radial grid configuration is then considered in this study.

3.2 The AVEREMS design optimization problem

As stated, when dealing with off-grid electrification systems based on renewable energies, hybrid systems and microgrids proved to be most reliable configurations: they can lead to an increase in efficiency and supply quality and a decrease in project cost (Yang et al., 2008; Kirubi et al., 2009; Alliance for Rural Electrification, 2011). The design of an off-grid electrification project considering hybrid systems and the combination of independent generation points and microgrids is the AVEREMS optimization problem.

In this Section the AVEREMS optimization problem is delineated: first the input data are defined (sub-Section 3.2.1), then the elements of a solution to the AVEREMS problem are described (sub-Section 3.2.2) and finally the objective function and constraints of the problem are presented (sub-Section 3.2.3).

3.2.1 Input data

Input data for an off-grid electrification project design could be divided into three types (Table 1): social, technical and resource data of the community.

The characteristics resulting from the social evaluation are: users' location, electrical energy and power demand of each user and the required days of autonomy of the batteries. The basic technical characteristics required are: technical data of generation, storage, control and distribution equipments; costs and efficiencies of all the equipments. Resource data refer to the daily energy production of all types of (wind and solar) generators in every possible generation point.

Table 1 – Main input data of the AVEREMS design optimization problem

	Data		Unit	Symbol
Social data	Location (of each user)		geographical coordinates	
	Energy demand (of user x)		Wh/day	ED_x
	Power demand (of user x)		W	PD_x
	Autonomy of the batteries		days	VB
Technical data	Generators	Number of generators' types		G
		Maximum power (of generator type g)	W	PG_g
		Cost (of generator type g)	$	CG_g
	Controllers	Number of controllers' types		R
		Maximum power (of controller type r)	W	PR_r
		Cost (of controller type r)	$	
	Batteries	Number of batteries' types		B
		Capacity (of battery type b)	Wh	EB_b
		Cost (of battery type b)	$	
		Maximum discharge rate	Fraction of unit	DB
		Efficiency	Fraction of unit	η_b
	Inverters	Number of inverters' types		I
		Maximum power (of inverter type i)	W	PI_i
		Cost (of inverter type i)	$	
		Efficiency	Fraction of unit	η_i
	Cables	Maximum intensity (of cable type c)	I	IC_c
		Resistivity (of cable type c)	Ωm	RC_c
		Cost (of cable type c)	$/m	CC_c
		Nominal voltage	V	V_N
		Maximum voltage	V	V_{max}
		Minimum voltage	V	V_{min}
		Efficiency	Fraction of unit	η_c
	Electric meters	Cost	$	
Resource data	Daily production of (each) generator type g in (each possible) generation point y		Wh/day	EG_{gy}

The social data results from an accurate evaluation that must be carried out by the project promoter in conjunction with final users in order to evaluate real electric energy uses and requirements. Technical characteristics of the various components are generally available if other similar projects were already implemented or a specific market study should be carried out to assess real costs in the context of the project. Regarding the resource assessment, the lowest resource period (e.g. one month) should be generally considered in order to carry out a conservative design (Zhou et al., 2010). The solar resource is commonly estimated by global or regional databases, such as the NASA one (NASA, 2011), and can be generally considered uniform at community scale (Gueymard and Wilcox, 2011). On the other side wind resource could vary considerably within the area of a community, especially in mountainous areas, thus detailed wind resource assessment is generally required (Alliance for Rural Electrification, 2011). The achievement of reliable and detailed wind data in isolated areas is one of the most critical input data. This issue is analyzed in detail in sub-Section 4.1 and Section 5.

3.2.2 Elements of a solution to the AVEREMS optimization problem

Figure 2 shows an example of a solution to the AVEREMS design optimization problem (or simply the AVEREMS problem) in a community of 22 users distributed on an area of 1 km x 1 km. For each generation point (green and red points of Figure 2), the number and type of generators, controllers, batteries and inverters (Figure 1) must be defined (minimizing the objective function and fulfilling the constraints of the generation system defined in sub-Section 3.2.3). Being an arch the segment of electric cable that connects 2 points of a microgrid and a branch the set of points and arches of a microgrid connected to the generation system passing from the same point (Figure 2), for each branch of a microgrid the type of cable to be used must be defined (minimizing the objective function and fulfilling the constraints of the distribution system defined in sub-Section 3.2.3).

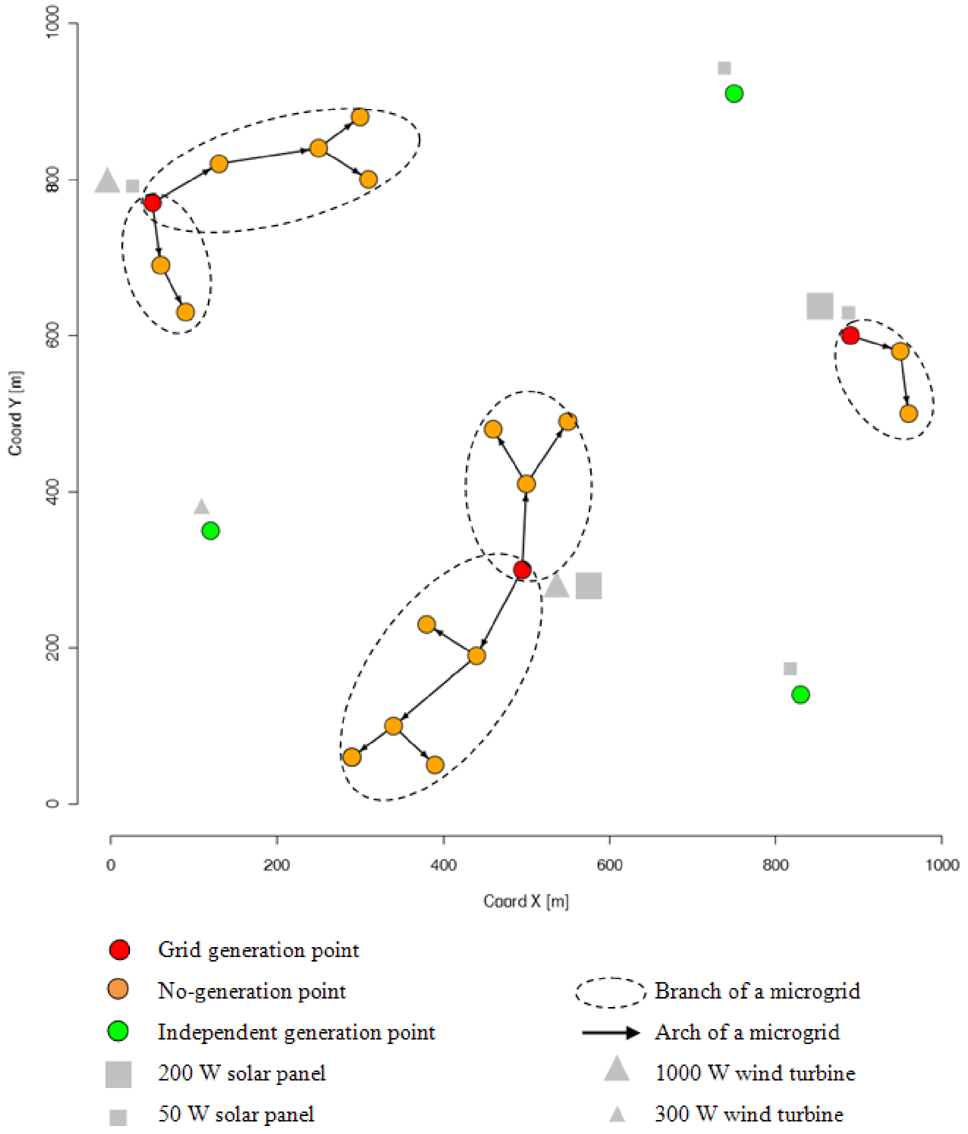

Figure 2 – Main elements of a solution to the AVEREMS problem

3.2.3 Objective function and constraints of the problem

The design of an off-grid electrification project using local available resources considering hybrid systems and microgrids is a hard combinatorial optimization problem (Ferrer-Martí et al., 2011). The aim is to find the lowest cost configuration, i.e. generation and distribution system design (Figure 2), which accomplishes with the energy and power demands of each user, taking into account energy resource maps and different technical constraints. The complete formulation of a mathematical model for solving the AVEREMS problem is presented in Ferrer-Martí et al. (2013), but considering generation only close to demand points. Next, the objective function of the AVEREMS problem and the main constraints of the generation and distribution systems (Figure 1) are resumed (symbols defined in Table 1 are used in equations (3.1) to (3.8)):

o Objective function: To minimize the cost of the project, considering all components defined in Figure 1, i.e. wind turbines, wind controllers, solar panels, solar controllers, batteries, inverters, meters, and cables.

o Constraints of the generation system:

- Generators (wind turbines and solar panels) must be adequately powered in order to cover the demand of all users connected to the generation systems considering the efficiencies of the different components. Batteries and inverters efficiencies are considered for all connected users, while cable efficiency is considered only for users located far from the generation point. Being y a generation point of solution s, GP_s the set of generation points of solution s, ng_{gy} the number of generators of type g installed in point y, G the number of generators' types, and UC_y the set of users connected by a microgrid to the point y (if point y is an independent generation point then $UC_y = ø$), the following equation must be accomplished

$$\sum_{g=1}^{G} ng_{gy} \cdot EG_{gy} \geq \frac{ED_y}{\eta_b \cdot \eta_i} + \frac{\sum_{k \in UC_y} ED_k}{\eta_b \cdot \eta_i \cdot \eta_c} \qquad y \in GP_s \qquad (3.1)$$

- Solar and wind controllers must be adequately powered according to the solar panels and wind turbines installed at the same point. Being y a generation point of solution s, GP_s the set of generation points of solution s, nr_{ry} the number of solar and wind controllers of type r installed in point y, the following equation must be accomplished for both solar and wind energies

$$\sum_{r=1}^{R} nr_{ry} \cdot PR_r \geq \sum_{g=1}^{G} ng_{gy} \cdot PG_g \qquad y \in GP_s \qquad (3.2)$$

- Batteries are forced to store enough energy to cover the demand of the supplied users, considering the required days of autonomy VB, the maximum permitted discharge DB and the efficiencies of the different components. Batteries and inverters efficiencies are considered for all connected users, while cable efficiency is considered only for users located far from the generation point. Being y a generation point of solution s, GP_s the set of generation points of solution s, nb_{by} the number of batteries of type b installed in point *y,* and UC_y the set of users connected by a microgrid to the point *y*, the following equation must be accomplished

$$\sum_{b=1}^{B} nb_{by} \cdot EB_b \geq \frac{VB}{DB} \cdot \left(\frac{ED_y}{\eta_b \cdot \eta_i} + \frac{\sum_{k \in UC_y} ED_k}{\eta_b \cdot \eta_i \cdot \eta_c} \right) \qquad y \in GP_s \qquad (3.3)$$

- Inverters type and quantity are determined according to users power demand. Being *y* a generation point of solution *s*, GP_s the set of generation points of solution *s*, ni_{iy} the number of inverters of type *i* installed in point *y* and UC_y the set of users connected by a microgrid to the point *y*, the following equation must be accomplished

$$\sum_{i=1}^{I} ni_{iy} \cdot PI_i \geq PD_y + \frac{\sum_{k \in UC_y} PD_k}{\eta_c} \qquad y \in GP_s \qquad (3.4)$$

o Constraints of the *distribution system*:

- The condition of radial scheme of the microgrids is imposed: each no-generation point must have one input cable; generation points cannot have any.
- The voltage drop is calculated according to formulas recommended in the mini-grid design manual of the United Nations (ESMAP, 2000). Being *a* an arch of a branch *b* (of a certain microgrid), A_b the set of arches of branch *b*, *c* the cable type used in branch *b* (the cable type is the same for all the arches of a branch), L_a the length of arch *a*, and DS_a the set of points of branch *b* that are downstream arch *a*, i.e. the energy they receive pass through arch *a*, the voltage drop along arch *a* is calculated as

$$\Delta V_a = RC_c \cdot \frac{L_a \cdot \sum_{k \in DS_a} \left(PD_k / \eta_c \right)}{V_N} \qquad a \in A_b \qquad (3.5)$$

- The maximum voltage drop must be satisfied in each branch considering cable electric resistivity. Being *w* and *z* two points of the same branch *b* of a certain microgrid, P_b the set of points of branch *b*, and ΔV_{wz} the voltage drop along the arch that connects points *w* and *z*, the following equation must be accomplished

$$\Delta V_{wz} \leq V_{\max} - V_{\min} \qquad w \in P_b\,,\ z \in P_b \qquad (3.6)$$

- The intensity flowing between two points connected by a cable cannot be higher than the maximum admissible intensity of the cable utilized. Being *a* an arch of branch *b*, A_b the set of arches of branch *b*, and DS_a the set of points of branch *b* that are downstream arch *a*, the intensity flowing along arch *a* is calculated as

$$I_a = \frac{\sum_{k \in DS_a} \left(PD_k / \eta_c \right)}{V_N} \qquad a \in A_b \qquad (3.7)$$

Being *c* the cable type used in branch *b*, the following equation must be accomplished

$$IC_c \geq I_a \qquad a \in A_b \qquad (3.8)$$

4. State-of-the-art

In this Section the state-of-the-art in the design of off-grid electrification projects with renewable energies is reviewed focusing on the available methods for wind resource assessment (sub-Section 4.1) and on the developed procedures to solve renewable energy related design optimization problems (sub-Section 4.2). In Section 4.3 the conclusions of the analysis of the state-of-the-art are reported identifying main lacks of the existing literature in designing AVEREMS projects.

4.1 Wind resource assessment for off-grid electrification projects

The proper identification of locally available renewable energy resources is a key issue in the design of off-grid rural electrification systems in order to improve effectiveness and long-term sustainability. Wind resource is the most critical to assess due to its high spatial and temporal variability.

Hereby, the methods currently utilized for wind resource assessment, such as global and regional databases (sub-Section 4.1.1), in-situ wind measurements (sub-Section 4.1.2) and micro-scale wind flow models (sub-Section 4.1.3), are briefly reported identifying the most adequate for rural electrification projects design. Finally the wind resource assessment carried out in literature off-grid electrification projects are described (sub-Section 4.1.4).

4.1.1 Global and regional databases

The most reliable methods to access wind resource assessment in a certain area when no on-site wind measurements are available are global or regional databases (Landberg et al., 2003). These databases are generally obtained simulating, by means of a combination of numerical models and historical wind data, the wind flow in the atmosphere during a long period, i.e. many years or decades. The result is a grid with (annual or monthly) mean wind speed and direction data in a whole area at a certain height above ground level (generally between 30 and 100 m a.g.l.) with certain spatial resolution (generally above 1 km). They could be classified into global databases that cover the whole world, such as the MERRA-NASA (Rienecker et al., 2011), and regional databases, such as Cape Verde (Risø National laboratory, 2007), Nicaragua (National Renewable Energy Laboratory, 2005) or Peru (Meteosim Truewind S.L., 2008) national wind maps. A recent and on-going collection of these databases can be found at the IRENA global atlas web site (IRENA, 2014).

The use of these data could be useful to better understand regional wind patterns and areas of high wind potential. However, they should not be directly used in evaluating wind resource at community scale in mountainous areas, as they cannot reach the required resolution (less than 100 m) and their uncertainty is generally high in assessing surface winds at 10-20 m a.g.l., i.e. the common hub height of small wind turbines.

4.1.2 In-*situ* wind measurements

The most common technique to assess wind resource in a specific area is generally by installing in-situ wind speed and direction measurements instruments. Regarding wind speed, the most adequate anemometers for rural electrification projects are cup anemometers constituted by 3 or 4 cups that are rotating around a vertical axis by means of wind action. Higher the rotating speed higher the wind speed. The accuracy of standard cup anemometers is around 0.1 m/s, thus around 5% at 2 m/s (Al-Abbadi and Rehman, 2009). For wind direction, a wind vane is installed close to the anemometer that orientates itself according to the direction where the wind comes from. Data should be taken every few seconds that are averaged every 10 minutes in order to work with statistically representative data (Rodríguez Amenedo et al., 2003).

4.1.3 Micro-scale wind flow models

In recent decades, a number of computer tools have been created to improve micro-scale wind resource assessment and their use is a de-facto standard, for instance, in wind farm design (Landberg et al., 2003). Micro-scale wind flow models are software tools that, starting from topographical and wind data (obtained by anemometer measurements or from global/regional databases), permit extrapolating wind data to a specific area around and thus obtaining a wind resource map of the interested zone. They can simulate detailed topographical configurations and reach the desired resolution to evaluate wind resource changes within a rural community (Landberg et al., 2003).

Different types of micro-scale models have been developed in the last two decades. Their basic functioning consists in resolving the Navier-Stokes equations that are the generally accepted mathematical formalization of the equations of mass, energy and momentum conservation (Rodríguez Amenedo et al., 2003). According to the assumed hypotheses and simplifications, micro-scale models can be classified into three types (Rodríguez Amenedo et al., 2003): CFD (computational fluid dynamics) models, which solve the complete Navier-Stokes equations with different turbulence simulation assumptions; linear flow models, which assume that the slope is small enough to linearize those equations; and mass conservation models, which solve only the continuity equation. In general, the improvements of CFD in comparison with simpler models have been demonstrated univocally only in highly complex terrains, whereas in many cases differences between these model types are limited (Llombart et al., 2007; VanLuvanee et al., 2009; Beaucage and Brower, 2012). The application of CFD models is thus not justified for small-scale community studies considering the major technical and calculation requirements that are rarely met in rural electrification projects. On the other side, due to their assumptions, linear and mass-conservation models are simpler and much faster than CFD models and can be run in common computers without high computational requirements.

4.1.4 Resource assessment in off-grid electrification projects

Rural electrification projects using wind energy in remote areas located far from the national electric grid have been implemented more consistently only in the past decade (Chongo Cuamba, 2009; Sompo Ceesay, 2009; Ferrer-Martí et al., 2010). In some projects, wind resource assessment and wind turbines production estimation for remote villages rely on statistical analyses of long-term wind data of nearest meteorological stations (Rehman et al., 2007; Raimundo et al., 2010;). In other projects, the resource assessments are based on anemometer measures at a point (Ferrer-Martí et al., 2010). When possible, anemometer data are combined with the information from national or regional wind atlases, like the Chilean experience (United Nations Development Program, 2011).

Recent projects showed that differences in wind resource could be significant within the users of a community located in mountainous area (Ferrer-Martí et al., 2009). This confirms that isolated wind measurements are not representative of the surrounding area in mountainous terrain, so there is a clear need for detailed micro-scale wind resource studies (with resolutions lower than 100 m).

4.2 Procedures to solve renewable energies design problems

The procedures for solving combinatorial optimization problems, such as the AVEREMS, are generally grouped into 2 classes: exact and heuristic methods (Blum and Roli, 2003). Exact methods, generally based on mathematical programming (Atamtürk and Savelsbergh, 2005), aim to explore all possible solutions and thus obtain the optimal one. However, due the non-linearity or the high number of variables of most real problems, these methods may not even find a feasible solution in a reasonable computational time. On the other side, heuristics methods aim to efficiently explore just a part of the solution space. Thus, heuristic (or approximate) methods sacrifice the guarantee of finding optimal solutions for the sake of getting good solutions in a significantly reduced amount of time (Blum and Roli, 2003).

Heuristic methods can group into “simple heuristics” and “metaheuristics”. Simple heuristics, such as greedy deterministic heuristics, are specialized procedures developed to solve specific combinatorial optimization problems. Metaheuristics, term defined by Glover (1986), refer to more general solution schemes that can be adapted to solve a particular problem or problem class (Gendreau and Potvin, 2005).

As stated, currently only two procedures have been proposed in literature that deal, even if with some limitations, with the AVEREMS design optimization problem (Lambert and Hittle, 2000; Ferrer-Martí et al., 2013). Limiting the analysis to these studies would result in a too short and undersized revision of the state-of-the-art on utilized solving procedures that deal with the analyzed optimization problem. In order to enlarge the range of considered studies, in this Section other optimization problems related with the design of renewable energy projects, for which much literature is available, are also analyzed focusing on the similarities with the AVEREMS problem and on the implemented solving procedures. The following 5 types of problems are considered (sub-Sections 4.2.1 to 4.2.5): Capacitated Plant Location Problem (CPLP); Wind farm design; Distributed generation networks design; Autonomous hybrid electrification systems design; and Autonomous hybrid and microgrids electrification systems design. The latter one is the most similar problem to the AVEREMS one and the two proposed solving procedures are revised in detail. In sub-Section 4.2.6 the conclusions of this analysis are reported. The considered studies encountered in literature for solving these 5 combinatorial problems are classified in Table 2 depending on the utilized solving procedure (exact or heuristic).

Table 2 - Procedures for solving the 5 analyzed optimization problems

Type of Problem	*Solving procedures*	
	Exact	Heuristics
Capacitated Plant Location Problem	- Cornuejols et al.(1991) - Sridharan (1995) - Zhu et al. (2010) - Mehdi et al. (2014)	- Jacobsen (1983), Sridharan (1995): Deterministic heuristics, LR - Delmaire et al. (1999): GRASP - Cortinhal and Captivo (2003); Sun (2012): TS - Arostegui Jr. et al. (2006): TS, SA, GA - Venables and Moscardini (2006): ACO - Chang et al. (2007): SA, VNLS - Contreras and Díaz (2008): GRASP, SS - Rahmani and MirHassani (2014): GA hybridized with another metaheuristic - Harris et al. (2014): LR + GA for multi-objective optimization
Wind farm design	- Archer et al. (2011)	- Ozturk and Norman (2004): Deterministic heuristics (ADD procedure) - Wan et al. (2012): PSO - González et al. (2011): Greedy (Prim, 1957) + GA - Saavedra-Moreno et al. (2011): Greedy + EA
Distributed generation networks design	- Khodr et al. (2002) - Wang and Nehrir (2004) - Gözel and Hocaoglu (2009) - Ghosh et al. (2010)	- Zhu et al. (1999): SA - Díaz-dorado et al. (2003); Celli et al. (2005); Cossi et al. (2005); Harrison et al. (2008); Carpinelli et al. (2010): GA - Mori and Iimura (2003); Cossi et al. (2009): TS - Khodr et al. (2010); Imran and Kowsalya (2014) : other metaheuristics
Autonomous hybrid system design	- Chedid and Rahman (1997) - Kanase-Patil et al. (2010)	- Shi et al. (2007); Zhou et al. (2008); Bernal-Agustín and Dufo-López (2009a, 2009b); Yang et al. (2009) : GA, EA - Hakimi and Moghaddas-Tafreshi (2009); Kashefi Kaviani et al. (2009): PSO - Ekren and Ekren (2010); Giannakoudis et al. (2010): SA - Menshsar et al. (2103): ACO
Autonomous hybrid and microgrids system design	- Ferrer-Martí et al. (2011, 2013)	- Lambert and Hittle (2000): Greedy + SA - Warner and Vogel (2008): ACO

ACO: Ant Colony Optimization
EA: Evolutionary Algorithm
GA: Genetic Algorithm
GRASP: Greedy Randomized Adaptive Search Procedure
LR: Lagrangean relaxation
PSO: Particle Swarm Optimization
SA: Simulated Annealing
SS: Scatter Search
TS: Tabu Search
VNLS: Variable Neighbourhood Local Search

As opposed to the other analyzed specific problems, the Capacitated Plant Location Problem (CPLP) is widely studied in the field of operational research (Mirchandani, 1990) as it is the generalization of different location optimization problems. Due to their broad range of applications, the most successful simple heuristics for solving the CPLP, such the ADD procedure (Table 2), are described in detail in sub-Section 4.2.1 as they have been used for solving some of the other problems and can be adapted to solve the AVEREMS problem. Most of other heuristic methods referenced in Table 2, such as Simulated Annealing (SA), Tabu Search (TS) or the Greedy Randomized Adaptive Search Procedure (GRASP), are metaheuristics; a description of the functioning of these metaheuristics can be found in Blum and Roli (2003), Gendreau and Potvin (2005), and Gogna and Tayal (2013).

4.2.1 Capacitated plant location problem

The location of plants to serve clients at minimum cost has been one of the most studied themes in the field of Operations Research (Mirchandani, 1990). The basic statement of the general location problem is: given a set of N clients with a given demand of a product and location and a set of M possible plants locations, find the number and location of plants to be opened and connections to be constructed in order to cover clients' demand minimizing a certain cost (or objective) function (Mirchandani, 1990). Depending on the objective function, there exist different types of the location problems: the most related with the AVEREMS one is the Plant Location Problem (PLP) that takes into account both installation and transport costs. When each plant has a capacity, i.e. a maximum amount of demand it can service, the problem is called the Capacitated PLP (CPLP).

Considering that each generator (solar panel or wind turbine) has a fixed amount of demand (energy) that it can cover at a fixed cost, many similarities between AVEREMS and CPLP problem could be identified. The product in the AVEREMS problem is the energy, the installation cost is the cost of the wind turbines and solar panels to be installed and the transport cost is the expense for the electrical network to be constructed. As wind resource is highly variable, there are as many capacitated plant types (amount of energy that the plant is able to supply) as many possible location points are considered multiplied for the number of wind turbine types. Main difference of the CPLP in comparison with the AVEREMS is the assumption that all the connections are between plants and clients (bipartite network) and no connections between clients (demand points) are considered. Therefore no network optimization is carried out. Batteries are not considered and fixed connections' cost are imposed (while in AVEREMS the unitary distribution cost depends on the type of cable used); battery capacity can be treated as an intermediate step between plants and clients as in supplier/plant/customer matching problems (Zhu et al., 2010).

The CPLP has been extensively studied and belongs to the NP-hard class of problem as demonstrated by Mirchandani (1990). Although algorithms to solve such problem optimally exist, they suffer from combinatorial explosion: in most cases, the time and computing resources required to solve such problems repeatedly in practical applications becomes prohibitive. Therefore, heuristics approaches have been widely utilized in literature, which are next briefly reviewed.

First heuristics for the CPLP were developed since 1950s and were basically greedy heuristics with simple local search methods (Sridharan, 1995). There are two different types of greedy heuristics for the CPLP, called ADD procedures and DROP procedures (Sridharan, 1995). These are the typical greedy construction heuristics: the former starts with no open plant and, in each iteration, adds (opens) the plant that brings maximum (if positive) savings in respect with current solution; the latter starts with all the plants opened and, in each iteration, drops (closes) the plant that brings maximum (if positive) savings in respect with current solution. The procedures stop when in one iteration maximum savings are negatives.

Some improvements to single ADD and DROP heuristics can be achieved by mean of interchange heuristics that apply a perturbation to the obtained solution and then reoptimize it (perturbation and reoptimization are repeated till the solution does not change). The most effective methods are those that combine ADD and DROP procedures, for example: a solution is firstly obtained by a DROP procedure, then a perturbation is made by means of ADDing (opening) a plant and finally the reoptimization is made by using a DROP iteration. Jacobsen (1983) verified that more complex approaches that combine different greedy and interchange heuristics did not result to make any improvement on the solution obtained by a single well design interchange heuristic.

As reported in Table 2, in the last decade various metaheuristics approaches have been developed and implemented for solving the CPLP with satisfactorily results (Arostegui Jr. et al., 2006; Contreras and Díaz, 2008). Most promising techniques are based on GRASP, TS, SA, VNLS and ACO. New solving methods, e.g. combining different metaheuristics (Harris et al., 2014; Rahmani and MirHassani, 2014), are currently under research.

4.2.2 Wind farm design

Due to recent developing of big wind turbines combined with the limited areas available, wind farm design optimization is a problem that has gained much attention in the last decade. The problem is basically the location of wind generators in a wind farm consisting of many generators with the objective of maximizing the profit (Aytun Ozturk and Norman, 2004), thus generally maximizing the total power output while minimizing the electrical connections to national grid and the required infrastructure. Other objective functions used in literature are reviewed by Serrano González et al. (2014). The main constraints are wake losses between wind turbines, due to blades rotation, and Joule losses in the wiring.

With respect to the AVEREMS problem, wind farm design optimization has some similar features, such as the need of wind resource map as input data and the minimization of the electrical network; on the other side, energy demand is not considered (as wind farm are connected to the national grid) and constraints as wake effects are of primary interest, while they are neglected in AVEREMS problem as the blades length of wind turbines is generally much lower in off-grid projects, i.e. maximum 5 meters blades of off-grid wind turbines in comparison with up to 50-70 meters blades of grid-connected wind turbines.

In literature only one example of exact method, based on a non-linear programming approach, was found to solve the wind farm design problem (Archer et al., 2011). In fact, when considering real situations and restrictions, the micro-sitting problem of wind turbines cannot be solved by exact methods (Serrano González et al., 2014). For this reason the techniques most commonly used have been metaheuristic procedures (Table 2). One of the most used and promising ideas is the combination of a metaheuristic procedure, such as genetic algorithms, with the Prim's algorithm for obtaining the minimum spanning tree (Prim, 1957) to minimize the civil infrastructure. The wind farm layout optimization is a really active field of research and further optimization techniques are expected to come out in the short future (Serrano González et al., 2014).

4.2.3 Distributed generation networks design

The design of electrical networks considering distributed generation is an interesting renewable energy related optimization problem. It is basically a location problem that defines the electrical system (i.e. networks, transformers, substations, capacitors, storage systems, etc.) in order to cope with the desired voltage, frequency and power requirements assuring certain supply quality and minimizing costs and power losses. Many electrical details and restriction are considered such as the power flow equations, transformers capacity, voltage drops and reactive power control. The location and sizing of distributed generations and their distribution networks is a complex non-linear constrained combinatorial optimization problem (Carpinelli et al., 2010).

In relation with the AVEREMS problem, main differences are basically that no wind resource map neither solar panels / wind turbines costs are considered in distributed generation and electrical networks optimization models. Furthermore, many others electrical characteristics and constraints considered by those models are not required in the design of AVEREMS.

This distributed generation networks problem can be solved by exact methods, such as those proposed by Khodr et al. (2002) and Ghosh et al. (2010). However, when applied to real situations (with a high number of variables), the computer calculation time can increase exponentially (Khodr et al., 2010). In this context, during last decades, heuristics and metaheuristics methods have been widely applied to solve the problem (Table 2). One of the most frequently used metaheuristics is the Genetic Algorithm (GA) that has been satisfactorily utilized for solving different versions of the problem (Carpinelli et al., 2010; Celli et al., 2005; Cossi et al., 2005; Harrison et al., 2008).

4.2.4 Autonomous hybrid electrification systems design

As stated, the combination of multiple technologies (hybrid systems) permits obtaining more reliable systems that are less affected by the fluctuations of a single resource. When considering multiple renewable technologies, the design of the system becomes more complex: the aim is to find the best combination of generation technologies (types and sizes), together with the definition of the required storage and control equipments (such as batteries and inverters), considering certain resource available resources in order to cover a certain energy and power demand. The optimal hybrid system configuration is generally the one that leads to the lowest lifetime cost and/or emission (Erdinc and Uzunoglu, 2012).

This design problem is the most similar problem to the AVEREMS problem, between the ones previously analyzed. The main difference in comparison with the AVEREMS is that a single generation point is considered, thus for example the distribution system is not designed, no wind resource map is utilized, etc.

The number of research papers that use optimization methods to solve renewable energy problems has increased considerably in recent years, especially for wind and solar energy systems (Baños et al., 2011). At present, much literature is available on the design of off-grid hybrid systems considering a certain demand and available resources (Bernal-Agustín and Dufo-López, 2009a; Erdinc and Uzunoglu, 2012; Luna-Rubio et al., 2012; Neves et al., 2014). Various softwares are currently available, such as iHOGA, HOMER, RETScreen and HYBRID2. Existing tools can be grouped into design (or sizing) tools, which defines the size and type of the various components in order to minimize/maximize a certain objective function, and simulation tools, which, from a certain configuration, simulates the behavior of the system considering demand fluctuations and other operational details (Bernal-Agustín and Dufo-López, 2009a; International Energy Agency, 2011; Sinha and Chandel, 2014).

Regarding the solving method, both exact and heuristic methods have been utilized in the last decades (see Table 2). However, due to the complexity of the problem, most exact methods shown to be inefficient to find the global optimum in comparison to well design metaheuristic methods (Erdinc and Uzunoglu, 2012). For this reason, a growing number of research papers tackle these problems using heuristic methods, and most softwares available are based on metaheuristic procedures, e.g. HOGA software (Bernal-Agustín et al., 2006). Most used approaches are Genetic Algorithms (Zhou et al., 2008; Yang et al., 2009) and Particle Swarm Optimization (Kashefi Kaviani et al., 2009). The hybrid renewable energy systems design is a really active field of research and further optimization techniques are expected to come out in the short future (Neves et al., 2014).

4.2.5 Autonomous hybrid and microgrids electrification systems design

Few attempts have been encountered in literature for the specific design of autonomous electrification systems through wind and solar energies with microgrids considering the real location of various demand points, spatial resource variations and the design of the distribution system.

A reference work in this field is the procedure developed by Lambert and Hittle (2000). The procedure presented draws upon the combination of two solving algorithms: a simple heuristic (based on the Prim modified minimum spanning tree algorithm) and a metaheuristic (based on the simulated annealing). The method is available in form of a user-friendly software called VIPOR that has been utilized for the design of stand-alone microgrids systems (Akella et al., 2007; Williams and Maher, 2008; Mitra, 2009). VIPOR designs the distribution system and defines generators locations, but does not optimize generation system components, such as generators, batteries, inverters and regulators. Thus it must be coupled with another tool that realizes this task, such as the HOMER software (Mitra, 2009). Other limitations of VIPOR are the limited number of possible generation points (maximum 10) and that a single microgrid connecting multiple users is present in the final solution. Approaches similar to the one of Lambert and Hittle (2000) have been utilized at a more regional level in order to decide which villages should be connected with the national grid and which not, as a function of the population density (Parshall et al., 2009).

Warner and Vogel (2008) propose a procedure for planning of electricity off-grid systems based on renewable energies: an optimal set of power plants and the optimal network structure for connecting the plants with consumers is searched in order to minimize the financial cost that includes investment and maintenance costs. Each demand point corresponds to a whole village and the infrastructure within it is not analyzed. The algorithm is based on an ACO metaheuristic. Besides having the same limitations of VIPOR, this procedure does not consider independent generation points.

Recently a mixed integer liner programming (MILP) model has been developed for solving the AVEREMS problem considering wind and solar power generation (Ferrer-Martí et al., 2013, 2011). The model optimizes the design and localization of microgrids, wind turbines and solar panels defining all electric components to be installed, taking into account voltage drops along the cables and resource variability. It has been successfully applied for the design of rural electrification projects in mountainous communities of Peru (Ferrer-Martí et al., 2013). Due to its high computational requirements, the application of the MILP model may be unreliable when the size of analyzed community (e.g. the number of demand points) increases. Furthermore, the model assumes that generation points must be located close to the users.

4.2.6 Final remarks of this analysis

As exposed, much literature is available on solving the five analyzed problems related with renewable energy projects design. The review focused on identifying main similarities of the considered problems with the AVEREMS and the most interesting solving procedures.

Regarding the similarities, Table 3 shows main characteristics of the AVEREMS problem (column 1) indicating which of those are considered in the 5 design problems previously analyzed (columns 2-7). Each analyzed problem considers some specific features of the AVEREMS design, but none takes into account all the different aspects of the problem.

Table 3 - Features of the AVEREMS problem that are considered in the 5 analyzed optimization problems

AVEREMS design problem	Capacitated Plant Location Problem	Wind farm design	Distributed generation networks design	Autonomous hybrid electrification systems design	Autonomous hybrid and microgrids electrification systems design	
					Lambert and Hittle (2000)	Ferrer-Martí et al. (2013)
Renewable energy application	X	X	X	X	X	X
Off-grid generation	X		X	X	X	X
Energy demand to be fulfilled	X		X	X	X	X
Independent generation points				X	X	X
Autonomous grids			X		X	X
Hybrid wind/solar generations				X	X	X
Batteries constraints	X		X	X	X	X
Electrical network optimization		X	X		X	X
Wind Resource map		X				X
Unlimited possible generation points	X	X				

The procedures that deal with the most similar problem are the ones proposed by Lambert and Hittle (2000) (VIPOR) and the MILP model proposed by Ferrer-Martí et al. (2013). However both methods have some limitations (resumed in Table 4). VIPOR only designs the distribution system and requires of an additional tool for generation system optimization. Other drawbacks of VIPOR, that reduce its range of application, are the limited pool size (10 as maximum) of possible grid generation points, the no-consideration of some electrical constraints, such as the voltage drop, and the assumption of a uniform resource in the area for independent generation points. The MILP model (Ferrer-Martí et al., 2013) designs both the generation and the distribution systems. In that model, possible grid generation points are restricted to be located at demand points, while higher resource areas could be located just a few tens of meters far from the demand (especially in mountainous areas where spatial wind resource variability could be really high). Furthermore, for large instances (e.g. high number of demand points) the exact method may not be computationally feasible, especially when different solutions should be analyzed and time and computational resourced are limited, as commonly in rural electrification projects design. The procedure developed in this thesis should overcome the weaknesses of existing procedures (last column of Table 4).

Table 4 - Differences between existing procedures (Ferrer-Martí et al., 2013; Lambert and Hittle, 2000) and the one proposed in this thesis (proposed procedure)

	Lambert and Hittle (2000)	*Ferrer-Martí et al. (2013)*	*Proposed procedure*
Optimized systems	🟥 Only distribution system	🟩 Generation and distribution systems	🟩 Generation and distribution systems
Computational requirements	🟩 Low (few minutes)	🟥 High (not feasible solutions for big instances in 1 hour)	🟩 Low (maximum 1 hour on common PCs)
Variable resource for independent generation	🟥 no	🟩 yes	🟩 yes
Low voltage network design	🟥 Maximum cable length	🟩 Voltage drop	🟩 Voltage drop
Maximum nº of grids in the solution	🟥 1	🟩 Not limited	🟩 Not limited
Maximum nº of possible grid generation points	🟥 10	🟥 Nº of demand points	🟩 Not limited

🟥 weakness 🟩 goodness

Regarding solving procedures, the literature review shows that methods based on heuristics and metaheuristics approaches are a rapidly growing field of research and they have been successfully implemented in last decades for all the analyzed problems (see Table 2). These approaches can normally handle larger instances that cannot be solved by exact methods and a good implementation is likely to provide optimal or near-optimal solutions in reasonable computation times. Different heuristic and metaheuristics procedures to efficiently solve analyzed problems were encountered in literature, such as greedy heuristics, ACO, GA, GRASP, SA and TS (Table 2). Hybrid algorithms combining 2 or more approaches showed to be highly effective in obtaining rapid solutions for large instance problems. As their performance is really problem specific, it is difficult to know a-priori which ones work better for the AVEREMS.

4.3 Analysis of the state-of-the-art

From the analysis of the wind resource assessment methods, it results that most implemented rural electrification projects considered a single (and thus uniform) resource in community area, estimated from the analysis of regional databases, of wind data from meteorological stations or from in-situ measurements. However, wind resource can vary considerably within the area of a community, thus proper wind resource assessment involves developing detailed wind resource mapping. In this sense, even if wind flow modeling is a de-facto standard in wind farm design to evaluate micro-scale resource variations, these tools are not used in off-grid rural electrification projects in remote areas in developing countries. From the analysis of existing models, it results that simpler models, i.e. linear and mass-conservation, are the most adequate for wind resource assessment in rural electrification projects due to their low computational requirements. However, these models were specifically designed for wind resource assessment in flat or smooth terrain where most grid-connected wind farms are located and there is the need of studies for analyzing their applicability in rural off-grid electrification projects' design.

After reviewing the procedures for solving optimization problems related with the design of renewable energy projects, it results that currently there are no methods for solving the Autonomous Village Electrification through Renewable Energy and Microgrid Systems (AVEREMS) considering all the different aspects of the problem. In particular, there is a lack of procedures for solving the AVEREMS considering generation in all points of community area (also far for demand points) with low computational requirements. Heuristic methods are currently successfully applied for solving similar problems and are a promising approach in solving AVEREMS problem. Furthermore, their limited computational time makes heuristic methods particularly adequate to cope with both the low resources generally available for rural electrification projects design and the requirement to evaluate multiple design options. A heuristic procedure specifically developed for solving the AVEREMS problem is thus needed in order to support the design of off-grid electrification projects with renewable energies and therefore improve their sustainability. As a starting point, it seems that a well designed deterministic heuristic composed by a construction step followed by a local search method is an appropriate strategy for solving related problems. More complex metaheuristic could be then developed to improve the deterministic algorithm.

5. Micro-scale wind resource assessment in off-grid electrification projects

As resulting from literature analysis (Section 4), most of rural electrification projects that utilize wind energy implemented in the last decade do not analyze micro-scale variations of the wind resource. However, especially in mountainous areas, wind resource may vary significantly between points of the same community, thus proper wind resource assessment involves developing detailed wind resource maps.

In this Section a procedure for wind resource assessment in rural off-grid electrification projects is proposed and validated in mountainous areas (sub-Section 5.1), and then it is applied to develop a detailed wind resource assessment for the design of a real community electrification project (sub-Section 5.2).

The complete description of this study presented in this Section can be found in the following papers reported in Annex 1:

- sub-Section 5.1 summarizes Ranaboldo et al. (2014a) “Ranaboldo M, Ferrer-Martí L, Velo E. Micro-scale wind resource assessment for off-grid electrification projects in rural communities. A case study in Peru. International Journal of Green Energy 2014;11(1):75-90”.
- sub-Section 5.2 summarizes Ranaboldo et al. (2014b) “Ranaboldo M, Domenech B, Vilar D, Ferrer-Martí L, Pastor R, García-Villoria A. Renewable energy projects to electrify rural communities in Cape Verde. Applied Energy, 2014;118:280–91”.

5.1 Procedure for micro-scale wind resource mapping

In order to carry out detailed wind resource mapping, various micro-scale wind flow models are currently available: they permit obtaining a detailed wind resource map of an interested zone from anemometer (or databases) wind data. Even if these models are widely used in wind farm design, their use is still minimal for off-grid rural electrification projects’ design.

As stated in Section 4, most adequate wind flow models for rural electrification projects are those that do not require huge computational requirements, such as mass-conservation or linear flow models. However, these models use as input data detailed topographic information and are specifically designed for wind resource assessment in flat terrain or smooth areas where most of grid-connected wind farms are located. In remote mountainous communities in developing countries terrain can be more abrupt than in wind farm areas and detailed wind and topographical data are often unavailable or inaccurate, and these limitations are preventing the use of these models in rural electrification projects. On the other side, the areas involved in the study are generally much smaller than wind farms areas (typical community areas are smaller than 20 square kilometres). Thus, considering these specific characteristics, micro-scale models performance should be analyzed and accuracy evaluated for their application in those projects.

Hereby, a procedure based on micro-scale wind flow modeling is proposed (sub-Section 5.1.1) and validated for wind resource assessment in rural off-grid electrification projects in mountainous areas (sub-Section 5.1.2).

5.1.1 Micro-scale wind flow model description

Among the several linear flow and mass-conservation models currently in use, we analyze WAsP 9 (Mortensen et al., 2007), developed by Risoe DTU, since is one of the most extensively used for micro-scale resource studies and much literature is available on its performances and limits (for a resume see Bowen et al. (2004)). Relying on the linear flow theory (Jackson and Hunt, 1975), the WAsP software generalizes a meteorological data series at a reference site on a wind atlas of the region, which may then be used to estimate conditions at other predicted sites.

Besides wind data, the input data required for calculations are mainly the topographic and roughness maps. The roughness is expressed as the aerodynamic roughness length, i.e. the height where wind speed is zero (Stull, 1988). Generally a uniform value can be considered defining specific areas with a different roughness, e.g. lagoons with zero roughness. The topographical map quality is an important parameter to ensure WAsP performance. WAsP literature recommends that the map should extend to at least 5 km from any point of evaluation in the predominant wind direction and the height contour interval should be less than 20 m (Mortensen et al., 2007) with lower interval closer to the evaluated area. Regarding the orographic context, a central parameter for defining the operational limits of the model is the ruggedness index (RIX) that indicates the fraction of the surrounding land above a critical slope (default 17°) (Bowen et al., 2004).

5.1.2 Analysis of model accuracy in mountainous communities

The accuracy of WAsP in mountainous context for rural electrification purpose was analyzed by applying the model for wind resource assessment in two communities (El Alumbre and Alto Peru) located in the northern Andes of Peru (Ranaboldo et al., 2014a). Both areas could be classified as medium complex terrain, i.e. RIX values around 10% in most of the area. Two anemometers were installed in each community (one in the upper part and one in the lower part of the community) at distance of around 2-3 km in order to carry out a cross-validation process. The data are simultaneously available from the two anemometers from December 2008 to March 2009 in El Alumbre and from March to May 2009 in Alto Peru. Monthly divided data are utilized in the analyses.

After carrying out a sensitivity analysis to evaluate input data detail requirements, it was verified that the topographical map has a significant influence on model performance. The purchased map has 25 m height contour interval (h.c.i.) lines. Specific software for height interpolation was used in order to obtain 10 m and 2 m h.c.i. lines. The wind flow simulation improves considerably if utilizing 10 m instead of 25 m h.c.i. lines; slight enhancements can be reached interpolating lines up to 2 m h.c.i. around project areas. The cross-validation also showed that the utilization of the anemometer in the lower part of the community as reference data could lead to considerable overestimations, thus it is recommended to install the anemometer in the upper part of the community.

When utilizing the anemometer in the upper part of the community as reference data and considering good topographic map (with h.c.i. lower that 10 m), the average mean error in absolute value is 5.5% in El Alumbre and 10.1% in Alto Peru. With a single exception (April 2009 in Alto Peru), errors are always lower than 7% in both communities. Hence, predictions can be considered highly accurate, in particular considering that the absolute error already assumed in wind measurements (around 5% for low wind speeds between 2 and 3 m/s) (Al-Abbadi and Rehman, 2009; Rodríguez Amenedo et al., 2003).

These results show good model performance and accurate resource evaluation for the distances involved. The application of a micro-scale model in estimating the wind resource in rural communities is thus highly recommended as it will help the promoters in optimizing the design of the projects, in reducing the uncertainty of supply problems related to wind technology and improving the effectiveness and impact of off-grid renewable energy projects.

5.2 Wind resource assessment case study

In this section, the application of the proposed procedure for a detailed wind resource assessment in a rural community in Cape Verde is described. As the followed resource assessment procedure is the same for the 2 projects analyzed in Ranaboldo et al. (2014b), hereby only the study carried out in Achada Leite (Santiago project) is described. Details of the other project can be found in Ranaboldo et al. (2014b) reported in Annex 1.

5.2.1 Community description

Cape Verde is a 10 islands archipelago located in the Atlantic Ocean with a total population of half a million people. Even though Cape Verde has high wind and solar energy resources, the conventional strategy for increasing access to electricity in isolated rural areas is by centralized microgrids with diesel generators (Chen et al., 2007; Raimundo et al., 2010).

Achada Leite is a rural community located in smooth hilly terrain area on the western coast of Santiago Island, the most populated island of Cape Verde. The community is composed by 42 houses and a school with a total population of around 90 inhabitants, distributed in an area of 0.3 km^2. Nowadays, no electrification systems are present; the closest connection to national grid is at around 3 km (Euclidean distance) in mountainous terrain.

The wind climate of Cape Verde is the typical of sub-tropical region with trade winds prevailing: in most sites dominant wind direction is from the northeast during the whole year. A meso-scale wind resource map of the country is available (Risø National laboratory, 2007) that gives information about mean wind speed and power density at 50 m with a modeling resolution of around 2.5 km. The wind resource in Achada Leite area is good with mean wind speeds at 50 m between 5 and 7 m/s.

5.2.2 Micro-scale wind resource study

As no wind measurements are available in Achada Leite, the closest data from the numerical wind atlas (Risø National laboratory, 2007) are used as input for the micro-scale analysis with WAsP 9 software (Mortensen et al., 2007). The available topographic map is sufficiently detailed with a height contour interval of 5 m. The wind resource is evaluated for an entire area within a radius of around 1 km around community houses. The used map extends to minimum 5 km around the studied area. RIX values are below 10% in the prevailing wind direction (N – NE), therefore WAsP modeling is expected to be reliable. A roughness length of 0.03 m is given to most land areas, composed by grass with few trees, while a palm forest located in the centre of the community is modeled with a higher roughness of 0.8 m and a null roughness length is assigned to the sea (Mortensen et al., 2007).

The wind resource is modelled at 20 m a.g.l. which is the proposed hub height of wind turbines (with nominal power between 600 to 7500 W). Different assessments were carried out using the 4 closest grid points of the meso-scale numerical wind atlas surrounding the studied areas. Then, as a conservative assumption, the meso-scale wind atlas which leads to the lowest wind resource in the analyzed area is considered. Finally, a decrease of 10% on the mean yearly wind speed is applied to wind climate average values (Risø National laboratory, 2007) in order to consider less windy season, i.e. summer (Gesto Energia SA., 2011; NASA, 2011).

Resulting wind resource map with a modeling resolution of 50 m (Figure 3) shows a high variability of resource in the analyzed area. Project area (black square in Figure 3) has a pretty low wind resource with mean wind speeds ranging from 2 m/s (in the palm forest area) to 3.5 m/s (at houses located at a higher elevation). Meanwhile, a higher wind resource area is located in the north of the community where a promontory is located close to the sea (black ellipse in Figure 3), therefore exploiting the trade winds blowing from north and north-east; mean wind speeds up to 6.5 m/s are present in this area.

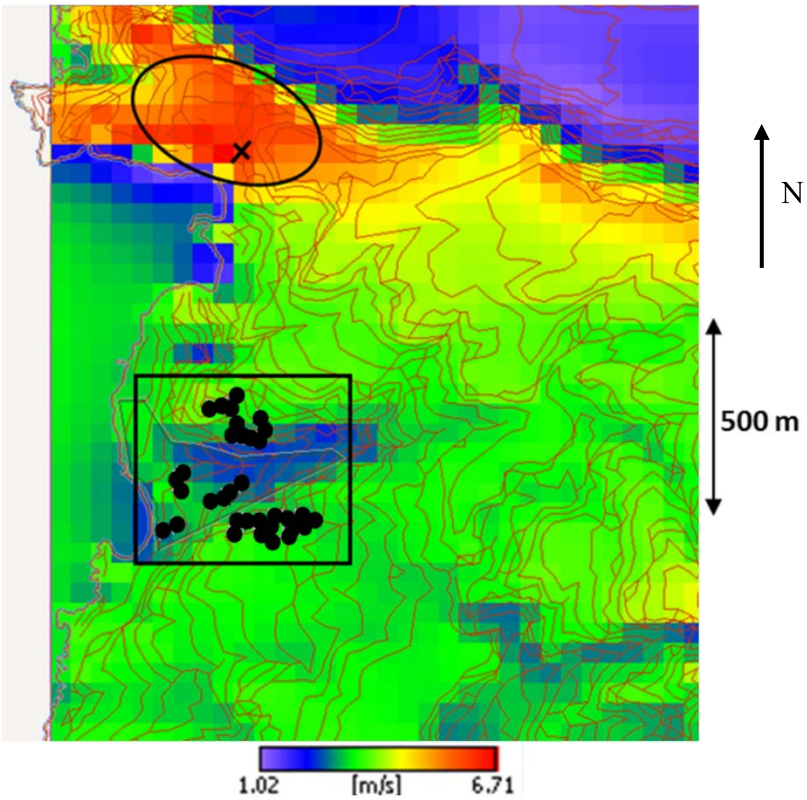

Figure 3- Mean wind speed at 20 m a.g.l. in Achada Leite. Community houses and school positions are shown by black circles. The "X" indicates the selected wind generation point

5.2.3 Project design

As houses are concentrated in a small area, the most adequate project configuration is the construction of a single grid connecting the whole community. Two different solutions were analyzed (obtained applying the MILP model of Ferrer-Martí et al. (2013)): one with generation close to demand point and the other considering generation in best resource area (point "X" of Figure 3) located far from the users. It was verified that the latter reduces initial investment of around 30% in comparison with the configuration that considers only generation in demand points. Therefore, the configuration consisting of a single microgrid with generation (two wind turbines of 3.5 kW and 7.5 kW nominal powers) in the no-demand point "X" Figure 3 is selected as the proposed design configuration.

An economic study was carried out to compare this configuration with the diesel generator configuration that is the conventional strategy in Cape Verde. Even if the proposed configuration has a higher initial investment cost, the diesel generator has much higher annual costs: the resulting payback time of the proposed configuration with respect to the diesel generator is around 11 years considering constant fuel costs (or 9 years as diesel fuel price increases 5% annually). Therefore, the proposed design configuration based on renewable energy is economically beneficial in comparison with a diesel generator based configuration as the expected lifespan of the project (minimum 15 years) is much longer than the payback time.

6. Development of procedures for solving the AVEREMS problem

As shown in the literature analysis (Section 4), heuristics procedures utilization seems to be particularly adequate for rural electrification project design since multiple design options should be evaluated, while limited time and computational resources are generally available.

This Section deals with the development of heuristic procedures to solve the AVEREMS design optimization problem considering generation in all points of the community area with low computational requirements. The instances utilized to carry out the experimental calculation analyze the performance of the developed procedures are described (sub-Section 6.1). Some indicators are firstly proposed in order to support algorithms design (sub-Section 6.2). Then the development of the heuristic and meta-heuristic procedures is presented (sub-Sections 6.3 and 6.4). Performance of the developed procedures is finally analyzed (sub-Section 6.5).

The complete description of this study presented in this Section can be found in the following papers reported in Annex 1 and Annex 2:

- sub-Section 6.2 summarizes Ranaboldo et al. (2013) "Ranaboldo M, Ferrer-Martí L, García-Villoria A, Pastor R. Heuristic indicators for the design of community off-grid electrification systems based on multiple renewable energies. Energy, 2013;50:501-12".
- sub-Section 6.3 summarizes Ranaboldo et al. (2014c) "Ranaboldo M, García-Villoria A, Ferrer-Martí L, Pastor R. A heuristic method to design autonomous village electrification projects with renewable energies. Energy 2014;73: 96-109"
- sub-Section 6.4 summarizes Ranaboldo et al. (2014d) Ranaboldo M, García-Villoria A, Ferrer-Martí L, Pastor R. A GRASP based method to design off-grid community electrification projects with renewable energies. Energy (1st revision)".
- sub-Section 6.5 summarizes the results of the performance comparison of Ranaboldo et al. (2014c, 2014d).

6.1 Generation of instances

Instances were randomly generated based on the characteristics of 5 real rural electrification projects: El Alumbre and Alto Perú (Peru), Achada Leite (Cape Verde), El Roblar and Sonzapote (Nicaragua). The characteristics of the generated instances are resumed in Table 5. Real projects wind and solar resource data are utilized in order to generate the instances. In each community the wind resource map of the area (with a grid spacing of 100 m) was obtained using a micro-scale wind flow model (Section 5). The solar resource is considered uniform within the areas of the projects. The electricity requirements of each user are 420Wh/day and 300W of energy and power demand respectively. The same electrical equipment defined in Ferrer-Martí et al. (2013) are considered.

According to the characteristics described in Table 5, two different set of instances were generated: 1) a "training set" of 90 instances for the calibration of the parameters internally used by the developed procedures; 2) a "test set" of 450 instances for comparing the performance of the developed procedures. The complete input data of these sets are available at https://www.ioc.upc.edu/EOLI/research/. All calculations carried out in this Section were done on a PC Intel Core 2 i7-2600 3.4 GHz with 8 GB of RAM.

Table 5 - Characteristics of the generated instances

Type of real project	Community	El Alumbre	Alto Perú	Achada Leite	El Roblar	Sonzapote
	Reference name	C1	C2	C3	C4	C5
	Area [km^2]	3.5 x 3.5	1.5 x 3.5	2 x 2	3 x 3	4 x 4
	Solar Resource [Peak Sun Hours]	4.3	4.3	4.8	4.2	4.3
	Wind speed [m/s]: min and max values of the map	2 – 6.5	1.5 – 4	1.1 – 7.5	1 – 10.2	0.9 – 9.7
Nº of users		10, 20, 30, 40, 50, 60, 70 80, 90				
Concentration of users		Low (25% of the users in 20% of the area) and High (50% of the users in 20% of the area)				

6.2 Heuristic indicators

Many heuristics (e.g. greedy) currently used to solve location optimization problems, such as the design of AVEREMS projects, divide the solving process into various steps; in each step an element is selected from an ordered list of possible candidates (i.e. candidate list) and included in the solution. In this Section, some heuristic indicators are proposed in order to rank the elements of a solution to the AVEREMS in an initial stage of the heuristic just relying on some a-priori characteristics of the studied community.

As shown in Figure 2, in a design solution to the AVEREMS problem three different types of points are present:

- Grid Generation Points: generation points of microgrids composed by multiple points';
- No-Generation Points (or grid consumption points): users connected to a multiple points' microgrid not being the generation point. They are just consuming energy.
- Independent Generation Points: demand points producing energy just for their own consumption and not connected to any multiple points' microgrid.

A priori, the identification of the characteristics of a point for being a Grid Generation Point, a No-Generation Point or an Independent Generation Point depends basically on the distribution of the energy resources (e.g. wind and solar) and of the users (demand distribution). In this sense, the following features are the most representative in order to characterize a single point: outstanding resource potential in comparison with the surrounding points and the energy demand concentration around the point. In the following the term "potential" is used as a synonym of resource and refers to the renewable energy potential in a specific site (not to be confused with the "electric potential").

Generally, a Grid Generation Point is located close to other demand points, so that it results reliable to connect them by a distribution network. Furthermore, it should have a high potential in comparison with the surrounding points, so that a-priori it seems better to install generators there instead of in closer points. Therefore a Grid Generation Point should have an outstanding potential and a high energy demand concentration around it. A No-Generation Point should also have a high demand concentration around it in order to be profitably connected by a distribution network, while it should have a lower potential in comparison with the surrounding points. On the other side, an Independent Generation Point should be isolated (low demand concentration around it) and its potential should be basically similar to the one of the surrounding points. Table 6 resumes those characteristics and proposes the two following indicators that evaluate the two features previously defined:

1) A Resource Indicator (*RI*) that evaluates how much the resource (potential) of a point outstands among the potential of the surrounding points. It does not correspond to the absolute potential of the point; instead it represents the relative potential of the point in comparison with the others. In Table 6, a "Positive" *RI* means that the point has a high potential, a "Null" *RI* means a similar potential and a "Negative" *RI* a low potential in comparison with the surrounding points.
2) A Demand Indicator (*DI*) that evaluates the demand concentration around the reference point considering the demand (and the number) of surrounding users weighted for their distance from the analyzed point. Its value is always positive and could be high or low.

Table 6 - Basic features of Grid Generation Points (GGP), No-Generation Points (NGP) and Independent Generation Points (IGP)

Indicator	*GGP*	*NGP*	*IGP*
Resource Indicator	High (Positive)	Low (Negative)	Null
Demand Indicator	High	High	Low

The Grid Generation Score (*GGS*), the No-Generation Score (*NGS*) and the Independent Generation Score (*IGS*), i.e. the indicators that evaluate the a-priori suitability of a point of being respectively a *GGP*, a *NGS* or an *IGP*, could be thus calculated as a combination of *RI* and *DI*.

A Hybrid Potential Indicator is firstly defined in order to consider different renewable energy resources (subsection 6.2.1); then *RI* and *DI* equations are described (subsection 6.2.2) and finally the calculation of the *GGS, NGS* and *IGS* (subsection 6.2.3) is proposed.

6.2.1 Hybrid Potential Indicator

When designing off-grid electrification projects based on hybrid renewable energy systems, it is fundamental to define a resource indicator that considers the multiple renewable resources that could be potentially exploited in an area. The levelized cost of electricity (*LCOE*) is the most often used criterion when comparing different electricity generation technologies (Branker et al., 2011). The *LCOE* is basically the ratio between the total cost of a project and the energy output expected through its lifetime. Following a similar approach, a potential indicator function *P()* for off-grid generation could be calculated as by equation (6.1).

$$P(ED) = \frac{ED}{CG(ED)} \tag{6.1}$$

ED is the energy demand to be supplied and function *CG(ED)* is the minimum generation cost, considering the best hybrid generators combination, in order to cope with that energy demand *ED*. For the function *CG()* calculation, all different combinations of hybrid generation (e.g. wind turbines and solar panels) are considered and the one with minimum cost is selected. Due to the economy of scale of most renewable energy technologies, the function *P()* is not constant and generally tends to increase with an increase in *ED*. As the energy demand to be covered from a reference point is not know a priori (how many demand points will be connected to a certain generation point), the function *P()* for a certain *ED* could not be directly utilized as the resource indicator.

For this reason it is proposed to utilize an indicator that corresponds to the average value of the function *P()* for different *ED* values. The different considered energy demands represent the different numbers of demand points that could be connected to the point where the generation system is installed. Therefore, the Hybrid Potential Indicator (*HPI*) of the point *i* is calculated as in equation (6.2):

$$HPI_i = \frac{\sum_{k=1}^{n_i} P\left(\sum_{j \in PP_i(k)} ED_j \right)}{n_i} \tag{6.2}$$

ED_j is the energy demand of point *j*, $PP_i(k)$ is the set of *k* users closest to point *i* (including *i*), n_i is the total number of users in a given radius L_{max} (maximum distance between the generation point and a demand point connected to it) around point *i* (including *i*).

6.2.2 Resource and Demand Indicators

As previously stated, the Resource Indicator (*RI*) should evaluate how much the potential of a point (reference point) outstands among the potential of the surrounding points. Considering a reference point i, potential differences with closest points should have a higher weight in comparison with potential differences with further points. Therefore, the relative potential of a point with respect to another could be calculated as the ratio between the potential difference and the distance between those 2 points. When considering a community, the Resource Indicator of a certain point i (RI_i^0, in equation (6.3)) is then the sum of the differences between HPI_i and HPI_j, considering all j demand points in a radius L_{max} around i (set N_i), divided by the distance L_{ij} between point i and j. In order to avoid unrealistic potential difference between really close points, e.g. resulting from uncertainties in GPS positioning or in the resource assessment procedure, a minimum distance L_{min} is established, so that all points closer that L_{min} to point i they are assumed to be at a distance L_{min}. Thus, being HPI_i an hybrid potential indicator that define the resource at point i considering multiple renewable energies, the Resource Indicator is calculated as

$$RI_i^0 = \sum_{j \in N_i} \frac{HPI_i - HPI_j}{\max\left(L_{ij}, L_{\min}\right)} \tag{6.3}$$

The Demand Indicator (*DI*) of a point i evaluates the demand concentration around the point (including the demand of the own point). Similarly to the Resource Indicator, its value should be weighted for the distance from the reference point for which the indicator is evaluated. Therefore, the Demand Indicator (DI_i^0 in equation (6.4)) is calculated as the sum of the ratios between the energy demands ED_j of the set N_i of demand points in a radius L_{max} around i (including point i) and the distance L_{ij} between point i and j. As for the Resource Indicator, a minimum distance L_{min} is considered to avoid exaggerating the influence of points located at a too small distance.

$$DI_i^0 = \sum_{j \in N_i} \frac{ED_j}{\max\left(L_{ij}, L_{\min}\right)} \tag{6.4}$$

Both the Resource and the Demand Indicators calculated as by equations (6.3) and (6.4) are normalized by their maximum and minimum values in the community, so that they can be combined for *GGS*, *NGS* and *IGS* calculations. The final indicators RI_i and DI_i range respectively from -1 to 1 and from 0 to 1.

6.2.3 Calculation of *GGS*, *NGS* and *IGS*

In the following, the calculation of the 3 specific indicators *GGS*, *NGS* and *IGS* that characterize the 3 types of points of an off-grid electrification projects (Figure 2) is described.

As previously stated (Table 6), the generation point of a microgrid composed by multiple points (*GGP*) should have a high potential in comparison with the surrounding points (positive Resource Indicator) and a high concentration of energy demand around it (high Demand Indicator). Therefore, the Grid Generation Score (*GGS*) should be in direct proportion with the Resource Indicator (*RI*) and with the Demand Indicator (*DI*). We propose the following way for the *GGS* calculation (equation (6.5)):

$$GGS_i = (\alpha + RI_i) \cdot (\beta + DI_i) \qquad \alpha \geq 1, \beta \geq 0 \qquad (6.5)$$

The *GGS* should take only positive values so that an increase in *DI* or *RI* means always an increase in *GGS*, therefore $\beta \geq 0$ and $\alpha \geq 1$. With $\alpha = 1$ the point with the lowest Resource Indicator ($RI = -1$) has also the lowest *GGS* ($GGS = 0$), this is a good assumption as it is clear that it will not be a good grid generation point. Regarding β coefficient, a null β value means that the point *Y* with the minimum Demand Indicator has also a null *GGS*. This is not a good assumption, as the point *Y* could have a high RI_Y and therefore being a reliable grid generation point even if it located far from other demand points. Assuming $\alpha = 1$, a sensitivity analysis has been carried out with β varying from 0 to 1. In the range $0.3 \leq \beta \leq 0.7$, the *GGS* value is stable and a β value of 0.5 is proposed. Hence, final *GGS* equation could be rewritten as in equation (6.6). Thus, the *GGS* value could range from 0 to 3.

$$GGS_i = (1 + RI_i) \cdot (0.5 + DI_i) \qquad (6.6)$$

The calculation of the *NGS* and *IGS* are discussed together and similar formulas for both indicators are proposed in order to make them easily comparable. In this manner, it is possible to evaluate which demand points are more suitable to be connected to a microgrid without being the generation point (*NGP*) and which should better be independent generation points (*IGP*).

As defined in Table 6, a *NGS* should have a low potential in comparison with the surrounding points (negative Resource Indicator) and a high demand concentration around the point (high Demand Indicator). On the other side, an *IGP* should have a low demand concentration around it (low Demand Indicator) and a similar potential in comparison with the surrounding points (ideally null Resource Indicator). Equations (6.7) and (6.8) are thus proposed for the calculations of the *NGS* and the *IGS* summing or resting the Resource and Demand Indicators depending if they are in direct or indirect relation with the indicators. In the *IGS* calculation the absolute value of *RI* (that ranges from -1 to 1) is considered in order to evaluate how much its value moves away from 0 (the best situation). In order to give the Resource and Demand Indicators similar weights, they are multiplied for the same coefficient (0.5). A unit is added to both indicators so that *NGS* and *IGS* are always positive (minimum null). Therefore, *NGS* and *IGS* values could range from 0 to 2, as by equations (6.7) and (6.8).

$$NGS_i = 1 - 0.5 \cdot RI_i + 0.5 \cdot DI_i \qquad (6.7)$$

$$IGS_i = 1 + 0.5 \cdot (1 - |RI_i|) - 0.5 \cdot DI_i \qquad (6.8)$$

6.3 Deterministic heuristic

Relying on the use of the indicators previously described, we propose a greedy deterministic heuristic that aims to obtain a good solution to the AVEREMS problem with low computational requirements. The main objective of the heuristic algorithm hereby proposed is to dispose of a fast method that could be easily used by promoters to support the design of those projects even in big rural communities (e.g. more than 50 users).

The proposed heuristic main structure is composed by 2 phases, as shown in Figure 4:

1) Construction

2) Local optimization

The "construction phase" refers to the construction of an initial solution. In this phase, the solution considering all independent generation points is firstly calculated, then the algorithm tries to extend micrograms as much as possible, according to the lowest cost criterion. The "local optimization phase" is composed by 2 steps that are repeated while the current solution is improved: firstly the microgrids are divided (if this brings to a better solution) into smaller ones and then the resulting microgrids are tried to be interconnected between them. Microgrids are always created following the minimum spanning tree procedure (Prim, 1957), which, given a set of users to connect, returns the configuration network that minimizes cables length.

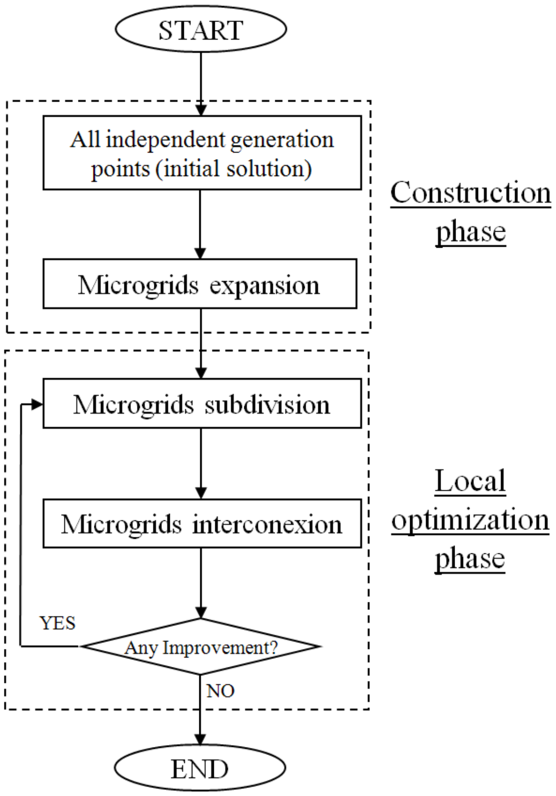

Figure 4 – Main structure of the deterministic heuristic algorithm

The whole heuristic can be seen as a multiple steps process in which microgrids expansion and microgrids reduction are subsequently carried out until no further improvements are obtained (Figure 4). It should be noted the microgrids expansion and reduction steps are conceptually similar to the ADD and DROP procedures (described in sub-Section 4.2.1) that have been widely applied in solving the CPLP: a combination of those procedures, i.e. the called "interchange heuristics", resulted to be a very efficient heuristic solution method.

After presenting a filter in order to screen the initial pool of possible generation points (sub-Section 6.3.1), the construction phase and the local optimization phase main structures are briefly described in sub-Sections 6.3.2 and 6.3.3. The selection of the best algorithm version is described in sub-Section 6.3.4.

6.3.1 Filter for pre-selection of possible generation points

The initial set of possible generation points far from the users could be potentially composed by every point of a certain area but is generally presented in form of a resource grid, i.e. the typical output of a micro-scale wind flow model (Section 5), with a certain grid spacing (e.g. 100 m). In an area of few square kilometres this set could thus contain more than 1000 points. In order to screen those that are not interesting a filter is proposed based on the Hybrid Potential Indicator (*HPI*) and the Grid Generation Score (*GGS*).

Being *D* the set of demand points and *IND* the set of initial (possible) no-demand points, the formal definition of set *ND* of pre-selected possible generation no-demand points is

$$ND = \left\{ i \in IND \,\middle|\, SEL(i, IND, D) \right\}$$

Where:

$SEL(i, ND, D)$	Boolean value that indicates if it exists at least one demand point *j* in the set *D* for which $E(i,j,ND,D)$ is false. If $SEL(i, ND, D)$ is true, the point *i* is selected as a possible no-demand generation point. $SEL(i,ND,D) = \exists j \in D \,\middle|\, \overline{E(i,j,ND,D)}$
$E(i, j, ND, D)$	Boolean value that indicates (for a no-demand point *i* and a demand point *j*) if it exists a no-demand point (in the set *ND*) or a demand point (in the set *D*) closer to *j* and with a higher *HPI* and *GGS* than *i*. $E(i,j,ND,D) = \exists q \in (ND \cup D) \,\middle|\, L(q,j) < L(i,j) \wedge HPI_q > HPI_i \wedge GGS_q > GGS_i$
$L(x,y)$	Distance between point *x* and *y*

Therefore, the number of pre-selected points depends on the number of users of the community and the number of initial no-demand points. In the test set of instances (sub-Section 6.1) with communities of 10 to 90 users and 400 to 1600 initial no-demand points, the filter reduces from 2 up to 15 times the number of possible no-demand generation points. The application of the filter in the Andean community of El Alumbre in Peru (Ferrer-Martí et al., 2010), is shown in Figure 5. Circle areas are proportional to their *HPI* value. In this case 290 points are pre-selected from an initial pool of 1296 no-demand points. It could be noted that, for instance, points with a low *HPI* located in the north-east and south-east of the community (in areas where demand points are not present) are discarded by the filter hereby presented (from now on called the "initial filter").

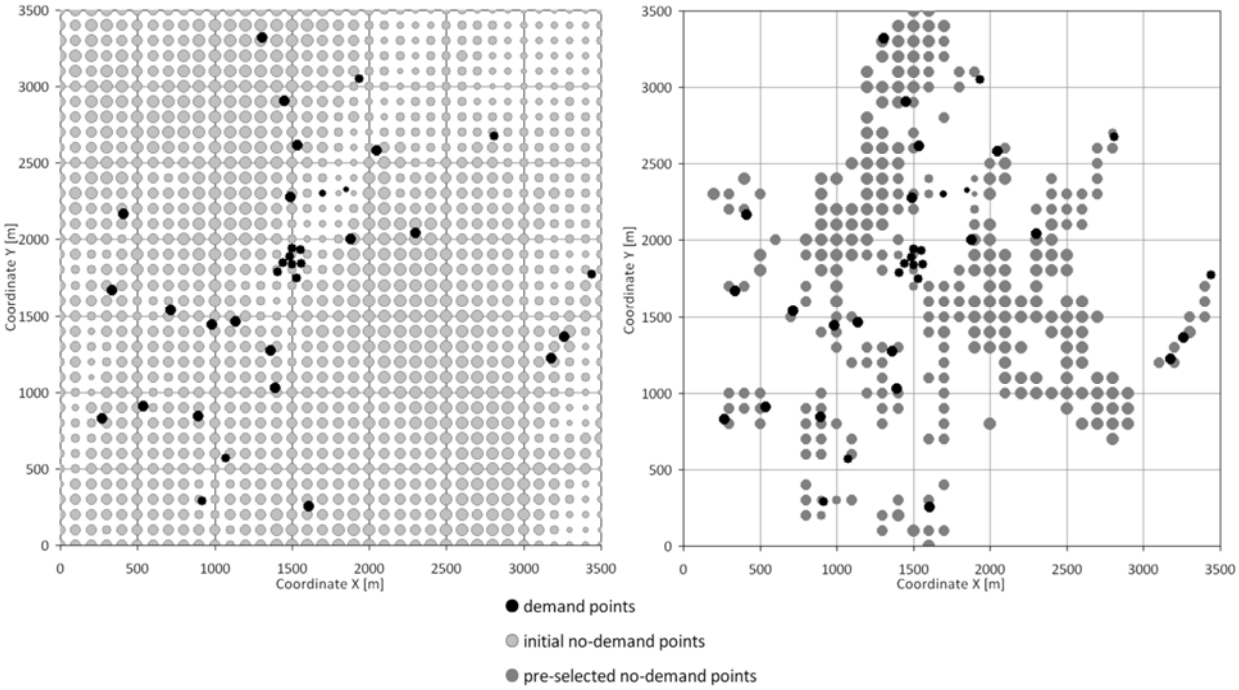

Figure 5 - Pre-selection of possible generation no-demand points in the community of El Alumbre

6.3.2 Construction phase

The construction phase main structure is shown in Figure 6. It is a deterministic algorithm composed by different iterations of microgrids' extension (cycle 1). In each iteration a microgrid (composed by one or more users) is extended: firstly the generation point is selected and then demand points are tried to be connected to the microgrid (cycle 2). The initial generation point of each microgrid is selected according to the *GGS* of the point. Users (or created microgrids) are then tried to be connected to the microgrid depending on a different criteria, i.e. three different "selection criteria" are proposed: 1) the distance; 2) the *NGS*, the *IGS* and the distance; 3) the savings. The connection is accepted if it leads to a cost decrease (or if the nº of users of the microgrid is equal or smaller than a predefined-calibrated value P_{min}) and then another point is tried to be connected. It is known that, due to the economy of scale (especially of wind energy), connections between users generally become economically beneficial only when the microgrid in expansion already connects a certain number of users. For this reason, a minimum number of users (parameter $P_{min} \geq 1$) are temporally tried to be connected to each microgrid, even if the cost increases. The extension of the microgrid (cycle 2) ends when the connection is rejected and then the extension of a new microgrid begins (new cycle 1). The algorithm ends when all the demand points of the community are part of an extended (created) microgrid. The least cost solution tried during algorithm run is finally returned.

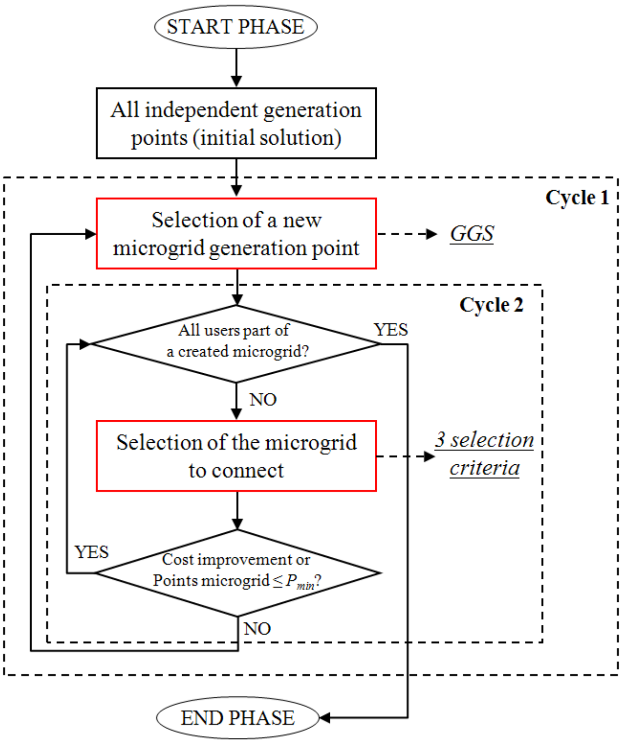

Figure 6 – Main structure of the construction phase

6.3.3 Local optimization phase

The local optimization phase is composed by two different processes:

1) Microgrids subdivision;
2) Microgrids interconnection.

The two processes are iteratively repeated while solution improves (i.e. the cost is reduced). Results in the 450 test instances (sub-Section 6.1) showed that the application of the "local optimization phase" results to be highly beneficial since it improves the solution obtained by the "construction phase" in around 50% of the instances (mean improvement around 1%) with an increased calculation time of less than 10%.

During microgrids subdivision phase, all the microgrids of the solution are tried to be subdivided into various microgrids. For each microgrid the following steps are carried out:

- The algorithm calculates the cost of dividing the microgrid into 2 smaller microgrids, eliminating one arch of the microgrid. All the arches of the microgrid (sorted in a decreasing order as a function of their cost) are tried to be eliminated.
- If the cost of the 2 new microgrids is lower than the cost of the initial microgrid then the sub-division is accepted. Therefore the same subdivision process is carried out for the 2 resulting microgrids.
- This process stops when no more subdivision is accepted.

During microgrids interconnection phase, all the microgrids of the current solution are tried to be interconnected. For each microgrid *m* the following steps are carried out:

- The microgrids located at distance to the microgrid *m* lower than their Break-Even Distance, i.e. the maximum distance at which a microgrid could be cost-effectively connected to another microgrid or to a no-demand generation point, are tried to be connected (separately) to *m*. The microgrid *mc* that leads to the highest cost savings is selected.
- If the connection between microgrids *m* and *mc* decreases the cost of the solution then the two microgrids are connected and the algorithm tries to connect another microgrid to the latter obtained microgrid.
- This process stops when the connection is rejected.

6.3.4 Selection of best algorithm version

Different algorithm versions (12 in total) are studied (Ranaboldo et al., 2014c) considering:

- the application or not of the initial filter for selecting possible generation points;
- *GGS*, *NGS* and *IGS* could be static (constant) or dynamic (variable in each iteration of cycle 1 or cycle 2 of Figure 6);
- the 3 criteria for selecting the point to be connected to the microgrid in expansion ("selection criteria" of Figure 6).

First the parameter P_{min}, i.e. the nº of users that are tried to be connected to the microgrid in expansion even if the cost decreases, is calibrated for the different algorithm versions on the training set of 90 instances (described in sub-Section 6.1).

Then the results of the different versions (with best P_{min} values) are compared in the test set of 450 instances (sub-Section 6.1): the use of static indicators and the application of the initial filter lead to better algorithm performance in comparison with dynamic indicators and no-filter. Regarding the 3 selection criteria, it is not evident which one is the most appropriate, as each one obtains the best solution depending on the analyzed instance. Thus the ensemble that returns the least cost solution of the launch of the 3 algorithm versions considering the 3 connection criteria (with static indicators and initial filter application), called "ESF" in Ranaboldo et al. (2014c), is analyzed. It obtains a solution that is only 0.25% worse than the one obtained by the ensemble of 12 algorithm versions, i.e. launching all the algorithm versions and returning the best found, but the computational time is around 10 times lower. Therefore, the ensemble ESF is finally selected as the proposed deterministic heuristic.

6.4 Metaheuristic

The heuristic method described in previous sub-Sections 6.3 is a deterministic procedure in which a single solution is constructed and then improved by a local search phase. However, the solution space of a problem, i.e. the set of all possible feasible solutions, is generally composed by multiple “valleys” or “basins of attraction” (Figure 7), i.e. the set of initial solutions which, after applying the improvement phase, converge to a certain solution (Blum and Roli, 2003). As shown in Figure 7, starting from an initial (constructed) solution (point “0”) and applying the improvement phase will forcedly lead to the basin of attraction of the valley at which point “0” belongs (point “1”). Point “1” is a local optimum, i.e. a solution that is optimal within all solution analyzed by the local search procedure; however this does not guarantee the quality of this solution in comparison with the global optimum, i.e. the best of all feasible solutions, that may be located in a different valley.

In the last few decades, various metaheuristic procedures have been developed in order to better explore the solution space, escape from local optima and therefore improve encountered solutions (Talbi, 2009). An effective metaheuristic to enlarge the search space introducing randomness in a deterministic greedy heuristic is the GRASP, Greedy Randomized Adaptive Search Procedure (Feo and Resende, 1995). GRASP based methods have been successfully applied to many location optimization problems (Festa and Resende, 2009), such as the capacitated plant location problem (Delmaire et al., 1999), which has many similarities with the AVEREMS problem (Section 4). A GRASP is a multi-start or iterative process, in which each iteration consists of two phases (Figure 7): solution construction, in which a feasible solution is produced using a randomized greedy algorithm, and solution improvement (or local search) which starts at the constructed solution and applies iterative improvement until a local optimum is found. Repeated applications of the randomized construction procedure yields diverse starting solutions for the local search and the best solution obtained in the process is kept as the result.

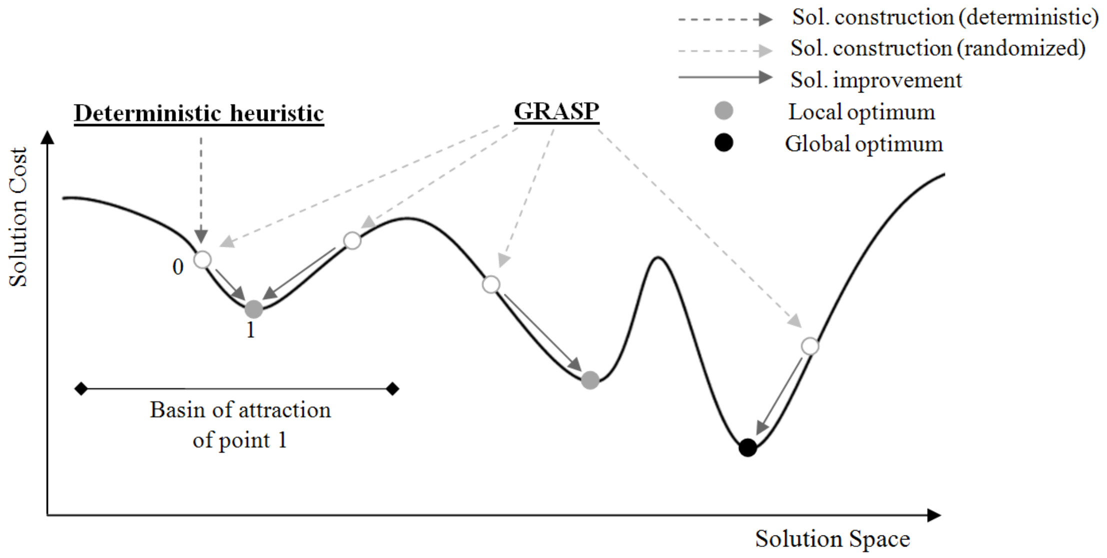

Figure 7 - Deterministic and GRASP methods main phases in the solution space of a minimization problem

In this Section, an enhancement to the deterministic heuristic is firstly described (sub-Section 6.4.1). Then a GRASP based procedure is developed starting from the enhanced deterministic heuristic (sub-Section 6.4.2). Finally the selection of the best GRASP based version is presented (sub-Section 6.4.3).

6.4.1 Enhanced deterministic heuristic

As stated in sub-Section 6.3, the deterministic heuristic creates microgrids always minimizing cables length. In many cases, this is the distribution configuration that leads to the lowest cost. However, in some communities it could be better, in order to reduce the distribution cost, to utilize a network configuration with a longer cable length (not the minimal) but that reduces voltage losses, and thus permits the installation of a less expensive cable type (lower cable unitary cost).

In order to take into account this issue, we propose an enhanced deterministic algorithm based on the previous one, which also includes an additional phase called “distribution system optimization phase” that aims to reduce distribution system cost. This new phase main steps are shown in Figure 8: firstly the branches of the microgrids of a previously obtained solution are tried to be subdivided (“Branches subdivision”) and then microgrids are iteratively tried to be interconnected, subdividing the branches of every new microgrid (“Microgrids interconexion with branches subdivision”).

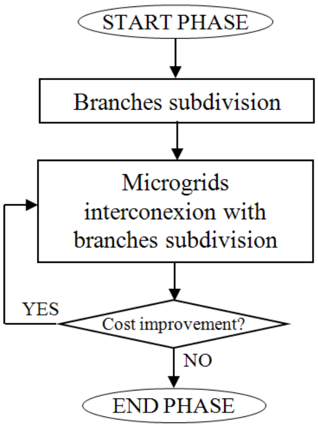

Figure 8 - Main structure of the distribution system optimization phase

The computational experiment (sub-Section 6.5.3) will show that this enhanced deterministic heuristic improves the solutions obtained by the initial deterministic heuristic (sub-Section 6.3) with a minimal increase in the calculation time. For this reason, the meta-heuristic next developed is based on the enhanced heuristic described in this sub-Section.

6.4.2 GRASP based algorithm

The enhanced deterministic heuristic is a greedy procedure in which a single solution is obtained in two main stages (Figure 9): solution construction (construction phase) and solution improvement (local optimization and distribution system optimization phases).

Hereby, a GRASP based algorithm is developed: each iteration is composed by the launch of a modified version of the enhanced deterministic heuristic with a randomized construction phase (Figure 9). As stopping criterion, a maximum calculation time or a maximum number of iterations can be defined. The best encountered solution is finally returned.

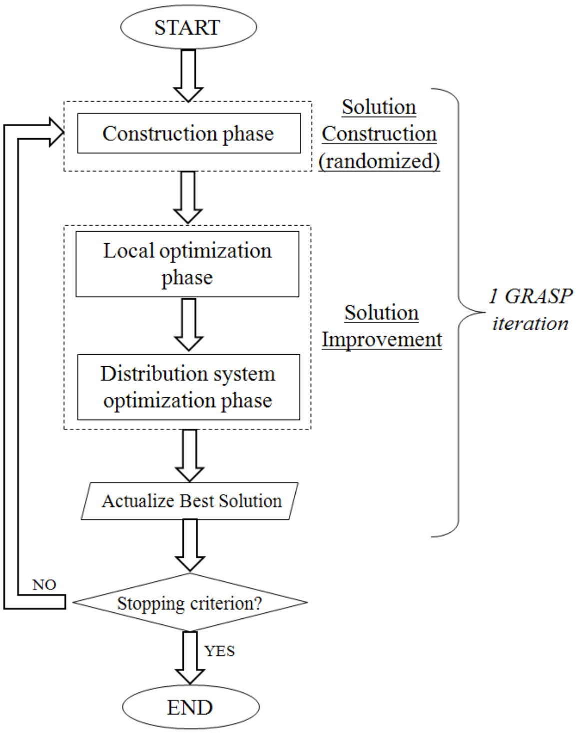

Figure 9 - Main structure of the GRASP based algorithm

As stated, the randomness of the GRASP is introduced in the solution construction phase in order to generate a wide range of different (and quite good) initial solutions and therefore improve the exploration of the solution space (Figure 7). Considering that a solution is composed by different elements that can be ranked by a heuristic function, the randomness can be introduced in the way (and order) these elements are iteratively added to the solution. In the deterministic construction phase, the best element, i.e. the one with the best value of the heuristic function, is always selected. In the randomized construction phase, part of the elements of the solution are ordered in a candidate list and then randomly chosen. The list of possible candidates is called the restricted candidate list (RCL) that is the key component in order to define the randomization.

The main steps of the construction phase are shown in Figure 6. Microgrids can therefore be seen as the different elements of a solution that are subsequently constructed in two iterative cycles: cycle 1 and cycle 2. The randomness could be therefore introduced in both cycles, defining two RCLs in “selection steps”, i.e. steps highlighted by red rectangles of Figure 6:

1) RCL1: list for the selection of the microgrid generation point (cycle 1).
2) RCL2: list for the selection of the microgrid to connect (cycle 2).

The main characteristics of the RCLs that are crucial in order to improve randomization efficiency and thus algorithm performance are: the heuristic function (to evaluate, rank and select the candidate elements) and the size (nº of elements contained in the RCL). The heuristic function (*HF*) is the indicator used to rank the set of all possible elements to be selected (*PE*). The *HF* also defines the probability of selecting an element from the RCL (in a proportional or inversely proportional way). According to the selection methods utilized in the deterministic construction procedure (sub-Section 6.3.2) the following *HF* are defined (the *GGS* for RCL1 and 3 selection criteria for RCL2):

1) HF_1: by *GGS* (proportional)
2) HF_{2a}: by distance (inversely proportional); HF_{2b}: by *NGS*, *IGS* and distance (proportional); HF_{2c}: by savings (proportional)

Regarding the size, the number of best ranked elements (*SE*) to be included in the RCL is defined as a proportion α (α_1 and α_2) of *PE*:

$$SE = \max\left(\left[\alpha \cdot |PE|\right], 1\right) \text{ with } 0 \le \alpha \le 1$$

where $[x]$ is the integer value closest to x.

6.4.3 Selection of the best algorithm version

As a-priori it is not known which of the 3 selection criteria for RCL2 works better, the performance of the following 6 GRASP based algorithm versions were analyzed:

- GRASP1: HF_{2a} is applied in each iteration (distance)
- GRASP2: HF_{2b} is applied in each iteration (*NGS*, *IGS* and distance)
- GRASP3: HF_{2c} is applied in each iteration (savings)
- GRASP4: HF_{2a}, HF_{2b} or HF_{2c} are randomly selected with the same probability in each iteration of Cycle 2 of the construction phase.
- GRASP5: HF_{2a}, HF_{2b} and HF_{2c} are alternatively applied in each GRASP iteration.
- GRASP0: no HF_1 neither HF_2 are used, i.e. totally random selection from RCL1 and RCL2 ($\alpha_1 = \alpha_2 = 1$ and $HF_1 = HF_2 =$ constant, e.g. 1), GRASP0 is analyzed to evaluate the importance of utilizing good heuristic functions.

The parameters $\alpha_1 = 0, 0.2, \ldots, 1$ and $\alpha_2 = 0, 0.2, \ldots, 1$ were calibrated, i.e. all combinations of values are tried except from $\alpha_1 = \alpha_2 = 0$, for the different algorithm versions (minus GRASP0) on the training set of 90 instances. The calibrated algorithm versions (with best α_1 and α_2 values) were compared on the test set of 450 instances (sub-Section 6.1) considering a computational time of 1 hour for each instance. As GRASP4 obtains the best results (e.g. least mean solution cost), it is finally selected as the proposed GRASP based algorithm.

6.5 Performance of the developed procedures

Hereby, we carried out a computational experiment in order to analyze the performance of developed procedures, which will be referred to as:

- IDH: the initial deterministic heuristic described in sub-Section 6.3 (called "ESF" in Ranaboldo et al. (2014c));
- EDH: the enhanced deterministic heuristic described in sub-Section 6.4.1;
- GRASP: the metaheuristic procedure described in sub-Sections 6.4.2 and 6.4.3.

In sub-Sections 6.5.1 and 6.5.2, the solutions of the initial deterministic heuristic (IDH) are compared with the ones obtained by VIPOR (Lambert and Hittle, 2000) and MILP model (Ferrer-Martí et al., 2013). As both VIPOR and MILP have some limitations in solving the AVEREMS problem (see sub-Section 4.2), some assumptions were done in order to make results comparable. Then the results of the 3 procedures proposed in previous sub-Sections (IDH, EDH and GRASP) are compared between them (sub-Section 6.5.3). The conclusions of these comparisons are finally reported (sub-Section 6.5.4).

6.5.1 Comparison with VIPOR

As introduced, the only heuristic procedure currently available for the design of off-grid community electrification projects considering resource variations and microgrid distribution is VIPOR (Lambert and Hittle, 2000), i.e. commonly utilized software for stand-alone microgrids design (Akella et al., 2007; Williams and Maher, 2008; Mitra, 2009).

However VIPOR have some limitations, thus in orders to obtain results comparable with IDH the following hypotheses were assumed:

- VIPOR defines the distribution system but does not design the generation system: it uses as input data, a predefined continuous generation – cost curve, i.e. generation cost as a function of the generated energy, for every possible generation point. On the other side, IDH considers a discrete curve as it designs both the generation and the distribution systems. In order to make consistent comparisons the following assumptions were done: from each obtained VIPOR solution configuration, the generation system is designed according to equations (3.1) to (3.4) of Section 3, as done by IDH; the continuous generation-cost curve for VIPOR was obtained calculating the generation system cost considering a variable energy demand when connecting one by one all the users.
- As VIPOR considers a single type of cable for low voltage distribution without calculating voltage losses, a single cable with null resistivity is also used by IDH.
- VIPOR limits to 10 the number of possible generation points. Two cases will be analyzed: pre-select the 10 points with higher wind resource (called "V1") or pre-select the 10 point with higher *GGS* (called "V2").

The solutions obtained by IDH and VIPOR (versions V1 and V2) in a selection of 50 instances of the test set are shown in Table 7. In each of the analyzed instances, the computational time of both methods is less than 180 s. In the last 4 columns of Table 7 the following data are presented: the mean difference between both solutions (“Difference” columns) and the number of instances in which IDH improves VIPOR solution by more than 5% (“Improv. > 5%” columns).

Table 7 - VIPOR and IDH solution costs (in US$)

		IDH	VIPOR		Comparison VIPOR – IDH			
			V1	V2	Comp. with V1		Comp. with V2	
		Sol. cost	Sol. cost	Sol. cost	Difference	Improv. > 5 %	Difference	Improv. > 5 %
Project type	C1	88951	95546	94644	6.4%	60%	5.0%	50%
	C2	95360	98355	100590	2.2%	10%	4.0%	40%
	C3	77991	87725	84377	7.6%	50%	5.9%	50%
	C4	82984	92918	90136	9.3%	70%	6.3%	50%
	C5	85800	93652	92544	7.2%	70%	6.6%	70%
Nº of users	10	19798	20418	20274	3.0%	20%	2.4%	20%
	30	55896	58751	57939	4.8%	40%	3.5%	20%
	50	87753	93887	94189	6.5%	60%	6.8%	70%
	70	119675	130099	127309	8.1%	60%	5.9%	60%
	90	147964	165041	162580	10.4%	80%	9.1%	90%
Users concentration	Low	87818	94257	93169	5.2%	36%	4.7%	44%
	High	84616	93022	91747	8.0%	68%	6.4%	60%
Total		86217	93639	92458	6.6%	52%	5.6%	52%

Regarding VIPOR solutions, version V2 performs on average better that version V1 in all project types’ a part from C2, where the lowest wind resource is present. This confirms the utility of the indicator *GGS* in pre-selecting most promising grid generation points, especially in sites with good wind resource. In no instances both VIPOR versions’ solution is more than 1% better than IDH solution. On the other side, IDH improves VIPOR solutions by more than 5% in around 50% of the instances with mean improvements around 6.6% and 5.6% in comparison with V1 and V2 respectively (Table 7).

The improvement of the IDH in comparison with VIPOR depends on the wind resource of the project, the number of users of the instance and the type of users’ concentration:

- Higher the wind resource higher the improvement: the lowest improvements (2.2% in comparison with V1) are obtained in instances C2 where the lowest wind resource is present, while highest improvements are obtained in C4 (9.3% in comparison with V1) which has highest wind resource. This correlation is probably due to the limited number of possible generation points as it is highly reduced when selecting those points by the *GGS* (version V2).
- As the size of the instance increases also the performance differences between VIPOR and IDH increase. In instances bigger than 30 users IDH enhances VIPOR by more than 5% in more than 50% of the instances.

- Higher improvements are obtained in instances with higher users' concentration: mean enhancements of 5.2% and 8.0% (in comparison with V1) are obtained respectively for the low and high users' concentration instances.

6.5.2 Comparison with MILP

Solutions of the IDH are hereby compared with the solutions obtained by the mixed integer linear programming (MILP) model described in Ferrer-Martí et al. (2013). The MILP model was solved using the IBM ILOG CPLEX 12.2 Optimizer considering a maximum computation time of 3600 seconds for each instance. As the MILP model considers just demand points as possible generation points, the same limitative hypothesis was assumed in the calculations with the IDH.

Table 8 presents the comparison between solutions obtained by the MILP model and the IDH on the test set. The MILP model and IDH mean solution costs and computational times are shown in columns 3-4 and 6-7 respectively. With respect to the MILP model solution, the difference between the solution cost and the lower bound found by the model (called "Gap") is presented (column 5). In the comparison between the MILP model and IDH, besides the mean difference between both solutions (column 8), the percentage of instances in which IDH improves MILP solution by more than 5% (column 9) and the percentage of instances in which the MILP model improves IDH solution by more than 5% (column 10) are presented.

Table 8 - MILP and IDH solution costs (in US$) and computational times (in seconds)

		MILP model			IDH		Comparison MILP – IDH		
		Sol. cost	Comp. time	Gap	Sol. cost	Comp. time	Diff.	Improv. IDH > 5%	Improv. MILP > 5%
Project Type	C1	94956	3203	20.5%	89981	3.9	3.2%	22.2%	0.0%
	C2	104212	3276	16.1%	99138	18.3	3.0%	27.8%	0.0%
	C3	98468	3213	27.4%	83651	7.4	8.0%	41.1%	0.0%
	C4	94287	3164	21.5%	86633	7.8	5.0%	33.3%	0.0%
	C5	88676	2992	16.2%	85505	5.1	2.3%	14.4%	0.0%
Nº of users	10	19929	172	0.0%	19944	0.4	-0.1%	0.0%	0.0%
	20	38379	3215	4.2%	38338	0.9	0.1%	0.0%	0.0%
	30	56634	3541	11.4%	56610	1.6	0.0%	0.0%	0.0%
	40	73881	3600	17.0%	73377	3.2	0.6%	2.0%	0.0%
	50	91171	3600	21.0%	89750	5.3	1.5%	8.0%	0.0%
	60	110000	3601	25.1%	106384	8.2	3.1%	14.0%	0.0%
	70	130944	3600	30.0%	122422	14.3	6.3%	52.0%	0.0%
	80	157381	3600	34.9%	139539	18.2	11.0%	82.0%	0.0%
	90	186756	3600	39.4%	154471	24.3	16.0%	92.0%	0.0%
Users concentration	Low	96633	3158	19.4%	89980	8.2	4.1%	28.0%	0.0%
	High	95607	3181	21.2%	87983	8.8	4.5%	27.6%	0.0%
Total		96120	3170	20.4%	88982	8.5	4.3%	27.8%	0.0%

The comparison between the MILP model and IDH solutions is highly dependent on the size of the instance. For instances of 10 users in which optimal solutions are always obtained by the MILP model (Gap = 0%), IDH solutions are nearly optimal with a mean cost difference lower than 0.1% with respect to the MILP model. For instances up to 40 users (in whose the Gap of the MILP model is lower than 20%) similar solutions are found by both procedures. However, in no instances the MILP model solution improves IDH solution by more than 5%. As the instance size increases the proposed heuristic finds better solutions in comparison with the MILP model with mean improvements of 1.5% in communities of 50 users and up to 16% for communities of 90 users. For instances of more than 60 users, the IDH enhances the MILP model by more the 5% in more than 50% of the cases.

The overall improvement of the IDH (with a computational time lower than 1 minute in all instances) in comparison with the MILP model (with a maximum computational time of 1 hour) is 4.3%. Finally it should be noted that if the computational time of the IDH is considered as the maximum MILP model computational time, no solution can be found by the MILP model in all analyzed instances.

6.5.3 Comparison between developed procedures

Hereby, the solutions of the developed deterministic (IDH and EDH) and metaheuristic (GRASP) procedures are compared. Besides demand points, all points of the wind resource map (see Table 5 of sub-Section 6.1) are considered as possible generation points. The results in the test set of 450 instances are shown in Figure 10 and Table 9.

Figure 10 shows the mean solution cost as function of the mean computational time of IDH and EDH (respectively the empty and the full black circles) and the convergence curve of the GRASP (grey line), i.e. the evolution of the cost of the best solution obtained over the computational time. Each point of the curve is the mean value of the solution costs in the 450 instances at different computational times. Table 9 presents the comparison between the 3 procedures for the different project types, nº of users and users' concentrations. The IDH, EDH and GRASP mean solution costs and computational times are shown in columns 3-4, 5-6 and 7-8 respectively. Column 9 shows the mean solution cost difference between GRASP and EDH and column 10 the percentage of instances in which GRASP improves EDH solution by more than 1%.

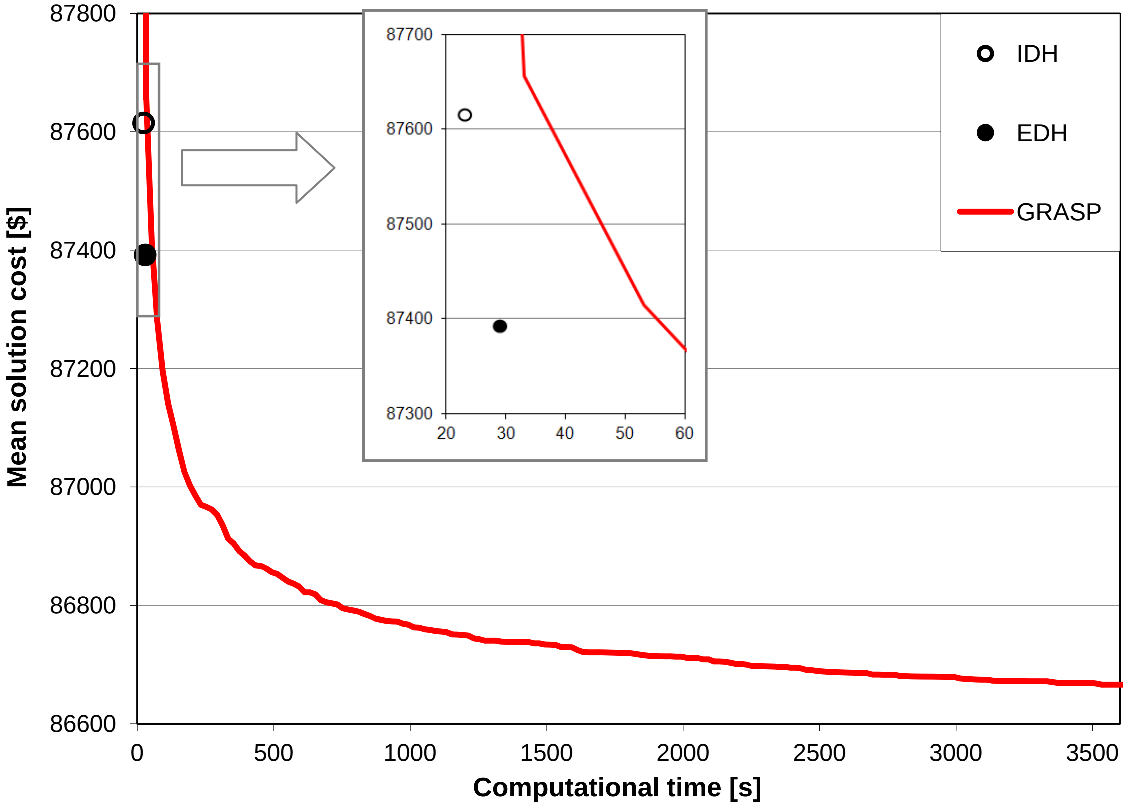

Figure 10 – IDH, EDH and GRASP solution costs as a function of the computational time

Table 9 - IDH, EDH and GRASP solution costs (in US$) and computational times (in seconds)

		IDH		EDH		GRASP		Compar. EDH - GRASP	
		Sol. cost	Comp. time	Sol. cost	Comp. time	Sol. cost	Comp. time	Diff.	Improv. GRASP > 1%
Project type	C1	89508	23.4	89426	28.8	88989	3600	0.4%	13.3%
	C2	97943	29.4	97908	34.3	96990	3600	0.7%	37.8%
	C3	82258	14.4	81470	23.7	80280	3600	1.1%	45.6%
	C4	84670	19.3	84543	25.3	83767	3600	0.7%	30.0%
	C5	83695	29.8	83615	33.5	83302	3600	0.3%	11.1%
Nº of users	10-30	37747	5.0	37744	5.3	37651	3600	0.2%	7.3%
	40-60	88492	19.9	88345	23.4	87697	3600	0.7%	30.7%
	70-90	136605	44.9	136089	58.7	134649	3600	1.0%	44.7%
Users concentration	low	88590	22.8	88381	28.2	87787	3600	0.5%	22.2%
	high	86640	23.7	86403	30.1	85545	3600	0.8%	32.9%
Total		87615	23.3	87392	29.1	86666	3600	0.65%	27.6%

As shown in Figure 10, the deterministic heuristics (IDH and EDH) can rapidly obtain a good solution, slightly better than the one found by the GRASP in the same computational time (see detail of Figure 10). When leaving a higher computational time, GRASP can obtain better solutions with most of the improvement reached in the first 1000 s, afterwards the curve tends to be horizontal (asymptote). As presented in Ranaboldo et al. (2014d), the time before reaching the asymptote (1000 s on average) depends on the complexity of the analyzed instance, e.g. increases as the nº of users of the community increases.

As shown in Table 9, EDH improves the solutions obtained by IDH (87392$ vs. 87615$), with a minimal increase in the computational time (29.1s vs. 23.3s). Therefore, EDH is the best developed deterministic heuristic; for this reason GRASP solutions are compared with EDH solutions in last columns of Table 9 (mention that GRASP (in a computational time of 3600 s) improves EDH in all instances expect one in which GRASP solution is 0.1% worse than EDH solution). The improvement of the GRASP in comparison with EDH depends on the number of users of the community, the size of community area and the type of users' concentration:

- As the number of users of the instance increases also the differences between EDH and GRASP increase. For instance of more than 30 users GRASP enhances new greedy by more than 1% in more than 20% of the instances. In instances between 70 and 90 users the mean improvement is around 1%.
- Higher improvements are obtained in instances with higher users' concentration: significant enhancements (more than 1%) are obtained in respectively 22% and 33% of the instances for the low and high users' concentration types.
- Smaller the community area higher the improvement: the lowest improvements (0.4% and 0.3% respectively) are obtained in C1 and C5 instances where users are dispersed over widest areas (12.25 and 16 km^2 respectively), whereas the highest improvements (1.1%) are obtained in C3, which has the smallest area of just 4 km^2.

6.5.4 Analysis of the results

From the analysis of the comparison with VIPOR and MILP, it can be concluded that the initial deterministic heuristic considerably enhances solutions obtained by both existing procedures. The enhancement was showed to be dependent on some characteristics of the studied instances: higher improvements are obtained when higher the wind resource, the nº of users or the users' concentration. These characteristics seem to be related with the possibility of generating bigger microgrids thus enlarging the solution space to explore: higher instance complexity higher the expected improvement. Moreover, as previously stated, both existing procedures have some limitations, i.e. VIPOR just focuses on the distribution system while the MILP model limits generation location close to the users, which are overcome by the proposed procedures.

Comparing the developed procedures, it was shown that the deterministic heuristics can rapidly obtain a good solution, slightly better than the one obtained by the GRASP in the same computational time. However, when a higher computational time is available, as it is expected when dealing with the design of a long-term project, GRASP can considerably enhance the solutions obtained by the deterministic procedures. Similarly to the previous comparison, this enhancement is dependent on the complexity (in terms of nº of users and users' concentration) of the analyzed instances.

7. Case study: design of a community electrification project in Nicaragua

In this Section we analyze the design study of the electrification project of Sonzapote, a rural community located in the central highlands of Nicaragua. The study includes a micro-scale wind resource assessment (as described in Section 5) and the application of the GRASP based algorithm (presented in Section 6) is used in order to support the design. The design hereby presented is the first detailed study of an off-grid electrification project with wind and solar energies at a micro-scale scale in Nicaragua.

Firstly the community is presented, analyzing main demand and techno-economical input data (sub-Section 7.1). A detailed wind resource assessment is then developed by means of in-situ wind measurements and a specific micro-scale wind flow model (sub-Section 7.2). The proposed design configuration obtained with the support of the GRASP based algorithm is finally described in detail (sub-Section 7.3).

The complete description of the study presented in this Section can be found in the following paper reported in Annex 2: Ranaboldo et al. (2014e) “Ranaboldo M, Reyes G, Domenech B, Ferrer-Martì L, Pastor R, Garcia-Villoria A. Off-grid electrification projects with renewable energies. A case study in Nicaragua. Applied Energy (1st revision)”.

7.1 Community description and input data

Nicaragua is a country of Central America covering an area between longitude 83-88º W and latitude 11-14.5º N. Nicaraguan west and east borders are respectively the Pacific Ocean and the Caribbean Sea. The analyzed community is Sonzapote (province of Boaco) in the central highland of Nicaragua (Figure 11). As shown in Figure 11, in the area around the community the wind resource is highly variable due to the complex topography with sites with good or even excellent resource (mean wind speed higher than 7 m/s at 50 m a.g.l.). The closest connection to the national electric grid is located at a distance of more the 3 km in hardly accessible terrain.

As stated in Section 2, input data required for the design of off-grid electrification projects can be divided into three types: demand, techno-economic and resource data. Next, the demand (sub-Section 7.1.1) and techno-economic (sub-Section 7.1.2) characteristics are reported. The wind resource assessment is described in sub-Section 7.2.

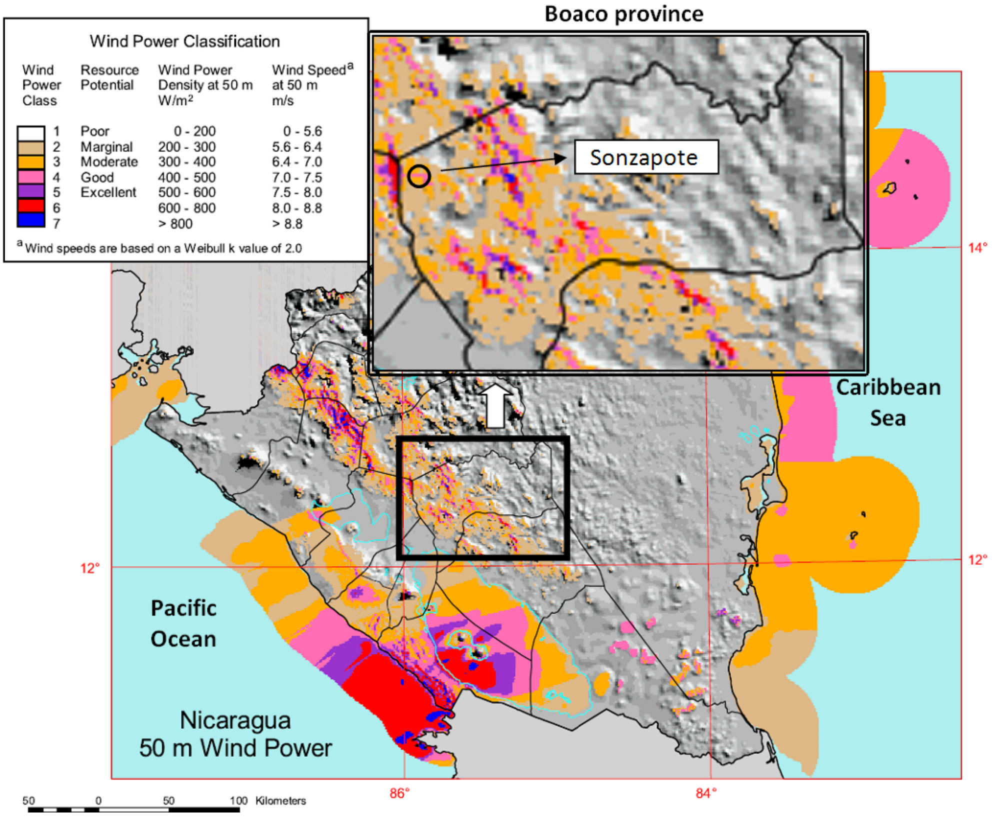

Figure 11 - Nicaragua topographical map with mean wind speed at 50 m a.g.l. (National Renewable Energy Laboratory, 2005)

7.1.1 Community energy requirements

Sonzapote is located at around 400-500 m above sea level (Figure 12, see legend in the bottom right). The community is composed by 83 houses, 4 mini-markets, 1 school and 1 church with a total population of around 345 inhabitants covering an area of 1 km^2 (Figure 12). The mini-markets sell primary alimentation products. The school is excluded from this study as it has already an electric supply for its consumption provided by solar panels.

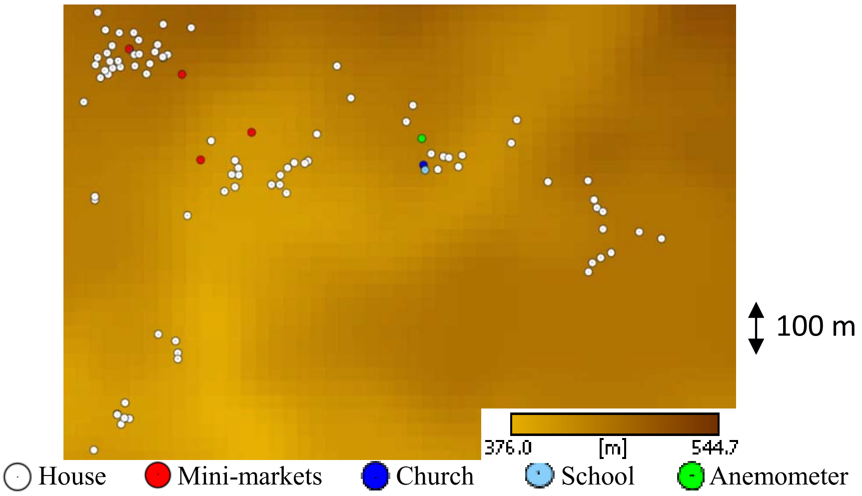

Figure 12 - Users locations in Sonzapote

The electrical energy and power demands of the different users were estimated by the promoter of Sonzapote project according to recently implemented electrification projects in the region (Table 10). Houses demand values in Table 10 correspond to 1 inhabitant per house; for houses with multiple inhabitants, increasing factors of +45 Wh/person·day and +15 W/person are applied respectively for energy and power demands.

Table 10 - Energy and power demand of the houses, the markets and the church in Sonzapote

Type of user	*Number of points*	*Energy demand [Wh/day]*	*Power demand [W]*
Houses	83	240	195
Markets	4	3975	660
Church	1	1500	900

7.1.2 Techno-economic data

The techno-economic characteristics hereby described refer to the definition of the technical and economical data of all the available components of the electrification project. As a long-term investment perspective is essential for developing successful projects (Alliance for Rural Electrification, 2011), the total life-cycle cost of a project is generally utilized when comparing different design alternatives (ESMAP, 2007; Short et al., 1995). Therefore for each component the present value of the total life-cycle cost (*TLCC*) can be calculated (Short et al., 1995) as:

$$TLCC = I + \sum_{n=1}^{N} \frac{O\&M_n}{(1+d)^n}$$

where: I is the initial investment [\$], $O\&M_n$ are the total operation and maintenance costs in the year n [\$], d is the nominal discount rate [%] and N is the project lifetime [years].

According to previous market studies (Marandin et al., 2013) and data provided by manufacturers and local NGOs, the initial investment costs and main characteristics of the equipment considered are the following:

- Wind turbines (5 types): nominal power: 200, 1050, 2400, 3500 and 7500 W; initial investment cost (include wind controllers): \$2273, \$11216, \$17861, \$25494 and \$67140.
- Solar panels (3 types): nominal power: 55, 250 and 2500 W; initial investment cost: \$329, \$916 and \$9158.
- Solar controllers (2 types): maximum power: 72 and 540 W; initial investment cost: \$65 and \$507.
- Batteries (2 types): capacity: 1290 and 2520 Wh/day; initial investment cost: \$141 and \$300; efficiency: 85%; autonomy: 2 days; minimum discharge rate: 0.6.
- Inverters (3 types): maximum power: 400, 1500 and 5000 W; initial investment cost: \$65, \$312 and \$1040; efficiency: 85%.

- Cables (4 types): resistivity: 2.416, 1.4, 0.964 and 0.604 Ω/km; maximum intensity: 70, 100, 150 and 205 A; cost (include posts): \$3.4/m, \$3.9/m, \$4.5/m and \$5.4/m; nominal voltage: 120 V; minimum voltage: 128.4 V; maximum voltage: 111.6 V.
- Electricity meter: cost: \$50 each (installed only in microgrids of multiple users).
- House for placing the generation system: \$600 (only microgrids of multiple users).

When included, the annual O&M costs of the various components are generally assumed to be a percentage with respect to their initial investment cost. Due to the significant variability of the O&M values encountered in literature (e.g. Bekele and Palm, 2010; Blechinger et al., 2014), different O&M costs scenarios are analyzed in Ranaboldo et al. (2104e) in order to assess how these can affect the selection of the most appropriate technology.

In next sub-Section 7.3, the finally proposed design configuration is described in detail. It is the one obtained with intermediate O&M costs (1.25% for solar and 2.5% for wind energy) that a-priori seems to be the most appropriate for Sonzapote: the community is not too far from the capital city and few community inhabitants are already trained to do small maintenance operations, as solar panels are already installed in the school.

7.2 Wind resource assessment

Regarding the solar resource, according to NASA database (NASA, 2011), in the region of Sonzapote the solar resource is pretty high with a mean global irradiance varying between 4.7 and 6.2 kWh/(m^2·day) along the year. In order to carry out a conservative analysis, the lowest resource month, i.e. November with 4.7 kWh/(m^2·day), is considered in this study.

Regarding the wind resource, the national wind atlas of Nicaragua (National Renewable Energy Laboratory, 2005) shown in Figure 11 gives information about mean wind speed and power density at 50 m with a grid spacing of 5.5 km. In the central Sierra of Nicaragua the wind resource is highly variable with some sites having moderate to excellent wind resource. Due to the complex topography of the area of Sonzapote, data from the National atlas could be not directly utilized to evaluate the wind resource at a community scale. Therefore, a detailed wind resource assessment was carried out including in-situ measurements and wind flow modeling (according to the procedure described in Section 5).

The analysis of global databases (NASA, 2011) and wind data from the closest meteorological stations showed that higher winds are present from December to April and lower winds from May to October, with a global minimum in September. Thus, in-situ wind measurements are carried out in September in order to analyze the lowest resource month. A standard three-cup anemometer with wind vane anemometer was installed in the centre of the community (see Figure 12) at a height of 8.5 m a.g.l., in an open-area close to the top of a small hill without surrounding obstacles. Wind speed and direction data were measured from the 1st till the 30th of September 2012 every second and mean value every 10 minutes were then registered by the instrument. The wind rose confirms the prevalence of trade winds with dominant wind direction from the northeast. Mean wind speed is 4.5 m/s with high diurnal variability: higher wind speeds are present during the day (6 m/s) while lower wind speeds during the night (3-3.5 m/s).

In order to evaluate the wind resource in the whole area of Sonzapote community a micro-scale analysis is carried out with specialized software, WAsP 9 (Mortensen et al. 2007). The available topographical map has a height contour interval of 10 m. According to the procedure defined in Section 5, the utilized map extended to more than 10 km in the prevailing wind direction (NE) and height contour lines were interpolated in order to reach an interval of 2 m in the area around the community. A roughness length of 0.2 m is given to most land areas, as terrain is composed by many low height trees, while a forest located in the centre of the community is modeled with a higher roughness of 0.8 m (Mortensen et al. 2007). In Sonzapote community most of the area has RIX values below 10%, therefore WAsP modeling is expected to be reliable.

Resulting wind resource map (Figure 13) shows a high variability of resource in the analyzed area. Users are located in areas with a medium wind resource with mean wind speeds ranging from 2.5 m/s (in the forest area) to 5 m/s (at houses located at a higher elevation) at 10 m a.g.l. Meanwhile, a smooth hill located in the south of the community (the red area in Figure 13) presents the highest wind resource with mean wind speeds up to 8 m/s.

7.3 Proposed design configuration

The GRASP based algorithm to optimize AVEREMS projects (presented in sub-Section 6.3) was used in order to properly support the design ("design algorithm"). The design algorithm was launched with a maximum calculation time of 5 hours, a lapse of time considered affordable taking into account the problem to be solved.

The proposed design configuration is composed by 3 microgrids composed by multiple users and 4 independent generation points (Figure 13):

- Microgrid 1 is based on wind energy: a wind turbine of 2.4 kW is installed in the top of the hill located in the south-east of Sonzapote with a mean wind speed around 8 m/s. The microgrid connects 3 groups of highly concentrated users (34 users in total) located in the east, centre and south-west of the community.
- Microgrids 2 and 3 are based on solar energy with nominal powers of 4.3 kW and 5 kW and connecting 22 and 28 users respectively. Generation points of both microgrids are located in users with maximum demand, i.e. mini-markets (see Figure 12).

- The 4 independent generation points (orange points) are users not connected to any microgrid having their own solar panels: P1 is an isolated house, while P2 and P3 are mini-markets that have their own generators in order to minimize energy losses. The connection of any of these points to microgrids 2 or 3 would increase project cost. Even if P0 is really close to the microgrid 3, it is slightly cheaper (around 100 $) to electrify P0 as an independent generation point than to connect it to the microgrid. However, when implementing the project, the promoter may connect P0 to microgrid 3 for practical and management reasons.

This configuration reduces the total life-cycle cost of the project of 16.4% in comparison with a design configuration considering all independent generation points. The proposed configuration combines independent systems, solar based microgrids and wind microgrids in order to connect concentrated groups of users, to take advantage of best wind resource areas and thus reducing the cost of the project.

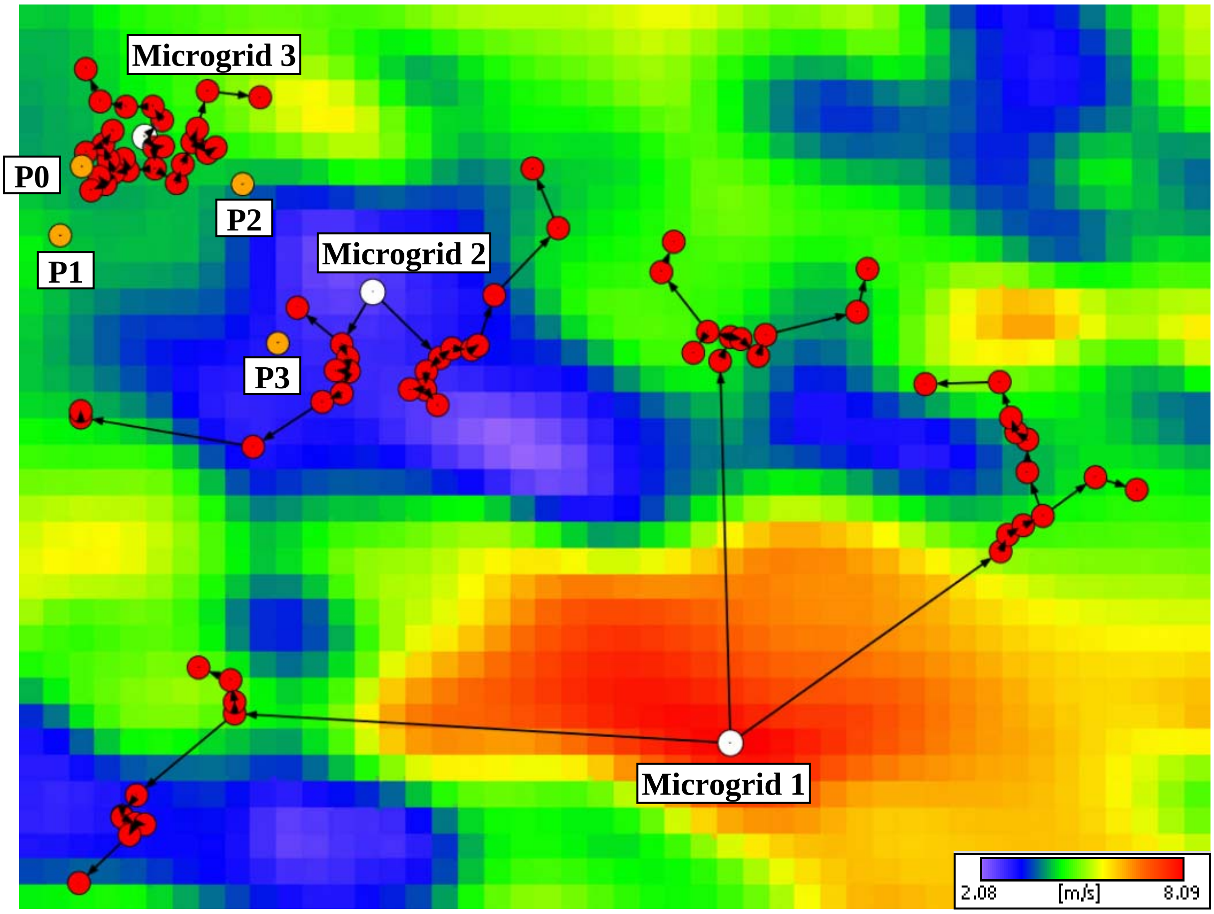

Figure 13 - Wind resource map at 10 m a.g.l. and the proposed design configuration in Sonzapote (white points are microgrid generation points, red points are the points connected to a microgrid, orange points are independent generation points)

8. Conclusions

The design of a community electrification project with renewable energies considering hybrid systems and the combination of independent generation points and microgrids (AVEREMS) is a complex optimization problem that is facing several issues. The objective of this thesis were to tackle some weaknesses of currently available methods for supporting the design of these projects, in particular the lack of knowledge regarding detailed wind resource assessment for rural electrification projects and the need of efficient procedures for solving the AVEREMS problem considering generation in every point of a community.

The objectives of this thesis have been achieved:

1) A procedure for micro-scale wind resource assessment for rural electrification projects has been defined and validated in mountainous communities
2) Different solving procedures have been developed: first some indicators were proposed in order to support the design of heuristic solving algorithms; then a deterministic heuristic and a metaheuristic algorithm were developed in order to solve the AVEREMS problem. The proposed algorithms, besides considering generation in every point of a certain area, enhance the performance of the currently available tools.
3) The design of a real electrification project in Nicaragua was presented including micro-scale wind resource assessment and the application of the developed metaheuristic optimization procedure.

The developed procedures aim to support the design process of off-grid rural electrification projects with renewable energies reducing some of the technical issues that still limit their implementation. The promoters will now dispose of tools that could be easily applied in order to obtain better design configurations, improve systems efficiency and sustainability, and thus enhance the social acceptance and help the dissemination of renewable energy projects.

In the following some possible future works are proposed:

- The developed solving procedures could be adapted in order to be included in a more general design methodology, such as the one proposed by Domenech (2013).
- In this thesis only wind and solar energies are considered. However, the solving procedures developed in this thesis could be modified to include other technologies, such as hydraulic or biomass.
- Some constraints of the distribution system can be improved. For example, only low voltage single-phase AC distribution is currently considered: in the future other types of distribution can be included, such as DC distribution or medium voltage.

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Ranaboldo M. Evaluacion de recursos. Alto Perú (Perú). In: Ferrer-Martí L, Cubells A, Velo E, Carrillo M. Proyectos de electrificación con energías renovables. Experiencias, lecciones aprendidas y retos de futuro. Icaria. Barcelona, 2013.

Annex A1. Articles published in journals included in the JCR index

Micro-scale wind resource assessment for off-grid electrification projects in rural communities. A case study in Peru

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Article published as [Ranaboldo M, Ferrer-Martí L, Velo E. Micro-scale wind resource assessment for off-grid electrification projects in rural communities. A case study in Peru. Journal of Green Energy 11 (2014) 75-90] © [copyright Taylor & Francis*]*

Abstract

The proper identification of locally available renewable energy resources are key issues in the project design of off-grid rural electrification systems in order to improve effectiveness and long-term sustainability. In recent decades, a number of computer tools have been created to improve micro-scale wind resource assessment and their use is a de-facto standard, for instance, in wind farm design. However, these tools are not used in off-grid rural electrification projects in remote areas in developing countries because some characteristics of the projects are out of models' operational limits (limited and inaccurate information available and steep terrains) and their applicability and performance in those contexts has not been studied. The aim of this study is to evaluate and optimise the performance of a micro-scale model for its application for resource estimation in rural electrification projects, considering their specific characteristics. The analyses are based on data collected in two communities in the Andean mountains of Peru. Sensitivity analyses are carried out to evaluate the influence of the main input data on assessment accuracy. Although limitations and constraints of these projects, the results show that the model performance is good and the resulting resource map is accurate in the typical area of a community project. Thus, analysed micro-scale model and procedure prove to be suitable for wind resource studies at the community scale; its use in the design of the electrification project of Alto Peru (Peru) is given as an example.

Keywords: Rural electrification; wind resource assessment; micro-scale models; off-grid generation; developing countries

1. Introduction

At present, over 1.5 billion people lack access to electricity (IEA, 2009) particularly affecting rural areas in developing countries (Kanagawa and Nakata, 2008). The natural strategy for increasing access to electricity in rural areas is to extend the electricity grid of the national interface system. However, in most rural areas, due to the extensive and complicated geographical conditions and the widespread presence of small villages, the expansion of the electricity grid would benefit a limited number of people in many countries. Under these circumstances, standalone electrification systems (off-grid generation) are a suitable option for providing electricity to these rural communities (Balamurugan et al., 2009). Generation options that exploit local renewable energy resources such as hydro, solar and wind energy can be used and can give isolated communities the opportunity to gain access to electricity in an autonomous, decentralized and sustainable manner (Zhou et al., 2010).

The choice of the energy technology depends largely on local resources available in each site. When possible, micro-hydro systems are the most widely used option (Coello et al., 2006). On the other side, wind technology can generally achieve a better installed kilowatt to installation cost ratio with respect to solar technology in areas where a sufficient wind resource is available. Rural electrification projects using wind energy in remote areas located far from the electric grid have been implemented more consistently only in the past decade (Chongo 2009, Sompo Ceesay 2009, Ferrer-Martí et al., 2010). In some projects, wind resource assessment and wind turbines production estimation for remote villages rely on statistical analyses of long-term wind data of nearest meteorological stations (Rehman and Halawani 1994, Rehman et al. 2007). In other projects, the resource assessments are based on anemometer measures at a point (Ferrer-Martí et al., 2010). When possible, anemometer data are combined with the information from national or regional wind atlases, like the Solar and Wind Energy Resource Assessment (UNEP, 2006) in Nicaragua. In Argentina, an important institutional effort was made to create a numerical model that has been implemented in rural electrification projects in Chubut (CREE, 2006). The Chilean experience (UNDP, 2011) is based on a regional wind atlas, developed by the National Renewable Energy Laboratory (USA), and on anemometer measurements. However, besides punctual measures at a point, proper wind resource assessment involves developing detailed wind maps that assess the wind resource available in each point of the community; especially in mountainous areas, wind resource may vary significantly between points of the same community.

In particular, these are some of the issues encountered in the electrification of windy mountainous communities in the Andean region of Peru (Ferrer-Martí et al., 2010). In 2007 Practical Action (Peru), Engineers without Borders (Spain) and Green Empowerment (USA) started to implement wind energy systems for rural electrification in a mountainous area in the north of Peru. The electrification of the first community, El Alumbre, concluded in January 2009 with the installation of small family wind turbines (Ferrer-Martí et al., 2010). Due to the high variability of the resource, it has been found that some users in El

Alumbre with house spacing of 100s m have more energy available than others, proving that differences in wind resource could be significant within a community. This confirms that isolated wind measurements are not representative of the surrounding area in mountainous terrain, so there is a clear need for detailed preliminary wind potential studies (with resolutions lower than 100 m).

Due to the different temporal and spatial scales involved and the dependency on many climatic and topographic factors, wind resource assessment is a complex task that involves the use of specific software for wind flow modelling. Wind mapping through the use of computer models is the de-facto standard in wind resource assessment at micro-scale for grid connected wind farms (Landberg et al., 2003). However, the requirements of some modern micro-scale models such as Computational Fluid Dynamics (CFD), in terms of computational time and resources could hardly be met in a rural electrification project design. Therefore this study focuses on simpler models, such as linear flow models. However, these models use as input data detailed topographic information and are specifically designed for wind resource assessment in flat terrain or smooth areas. In remote mountainous communities in developing countries terrain can be more abrupt than in wind farm areas and detailed wind and topographical data are often unavailable or inaccurate, and these limitations are preventing the use of these models in rural electrification projects. On the other side, area involved in the study could be much smaller than wind farms areas (typical community areas are around 5-20 square kilometres). Thus, considering these specific characteristics, micro-scale models performance should be analysed and accuracy evaluated for their application in those projects.

The objectives of this study are the analysis of available models for wind resource assessment at community scale and the validation of a procedure for wind resource assessment in rural off-grid electrification projects in mountainous areas. Firstly, wind resource assessment methods are analysed in order to identify the tools that are most suitable for micro-scale assessment and rural electrification purpose. A linear flow model (WAsP) is examined in more detail focussing on its main limitations and on the appropriate pre-process of input data. Model accuracy is then evaluated through its application to the study of two communities in the Andean mountains of Peru. Results of this study show good model accuracy and thus open the doors to the use of these models in rural electrification projects. In particular, the results of the wind resource assessment described in this study were used for the electrification design in the community of Alto Peru. The rest of the paper is organized as follows. In Section 2, a comparison between micro-scale models is carried out and utilized model is described. Section 3 presents the data used in the two case studies in Peru. Performance evaluation and application of the proposed model are described in Section 4, and Section 5 deals with the conclusions.

2. Micro-scale flow models for rural electrification

There are methods to access wind resource assessment in a certain area when no on-site wind measurements are available: traditional methods, global databases or meso-scale modelling (Landberg et al., 2003). Most important results of the combination of global databases and meso-scale modelling are national or regional wind resource maps (wind atlas), as the wind atlas of Peru that contains wind velocities and power densities at 50, 80 and 100 m above ground, with a resolution of 1 km (Meteosim, 2008). The use of these methods and data could be useful to better understand regional wind patterns and areas of high wind potential. However, they could not be directly used in evaluating wind resource at community scale in mountainous areas, as the required resolution (less than 100 m) could hardly be reached and their uncertainty is still high in sites with complex topography. Therefore, on-site measurements are required for resource assessments in rural electrification projects.

Combination of meso-scale and micro-scale models, which simulate wind flow at a much higher resolution based on anemometer data, is a powerful tool for wind resource assessment (Landberg et al., 2003). However it is very time- and resource-consuming, with a computing time up to one week on modern computing processing systems (Reed et al., 2004). Furthermore, a recent comparison between a state-of-the-art meso-micro scale model and a commercial micro-scale model, which runs in a few hours, showed that for distances under a few kilometres (typical community scale dimensions) the differences between the results of the two models are limited (Reed et al., 2004). The improvements in the resource assessment compared with the time and computational resources required are not sufficient to justify their use for rural electrification purpose (in case on-site wind measurements are available).

2.1 Micro-scale models comparison

This study focuses on the analysis of micro-scale models, which can simulate detailed topographical configuration and reach the desired resolution to evaluate the changes in wind potential in a rural community.

Different types of micro-scale models have been developed in the last two decades. Their basic functioning consists in resolving the Navier-Stokes equations that are the generally accepted mathematical formalization of the equations of mass, energy and momentum conservation (Rodriguez et al., 2003). According to the assumed hypotheses and simplifications, micro-scale models can be classified into three types (Rodriguez et al., 2003): CFD models, which solve the complete Navier-Stokes equations with different turbulence simulation assumptions; linear flow models, which assume that the slope is small enough to linearize those equations; and mass conservation models, which solve only the continuity equation. CFD models are the most complete and may offer a physically more realistic view of the wind and turbulence field. However, the computational effort required by these models is significant and they require a very high resolution to ensure an accurate assessment (Llombart et al., 2007). Therefore, the calculation time remains a constraint if modern technology and highly costly computation tools are not available. Furthermore, considerable uncertainty is still associated with the quantification of turbulence and its effects on main flow (Berge et al., 2006). In recent years, studies have been conducted comparing CFD and linear flow models to evaluate the effective need to use more complicated models (for examples see Llombart et al. 2007, Berge et al. 2006, Moreno et al. 2003). In general, the improvements of CFD in comparison with simpler models have been demonstrated univocally only in highly complex terrains, whereas in many cases differences between both model types are negligible. Therefore, the application of CFD models is not justified for small-scale community studies considering the major technical and calculation requirements that are rarely met in rural electrification programs.

Due to their assumptions, the other two types of models are much simpler and faster than CFD models and can be used by commercial processors without special computational requirements. Linear flow models physical basis derives from Jackson and Hunt theory (Jackson and Hunt, 1975), recently reviewed by Belcher and Hunt (1998). Main limitations of the linear model implemented in this study are discussed in next section. Mass conservation models are the simplest as momentum and energy conservations are disregarded and generally multiple on-site measurements are required (Rodriguez et al., 2003). Comparison at Blashaval Hill international experiment shown that linear flow models generally perform slightly better than mass-conservation models over complex terrain (Walmsley et al., 1990). Therefore, linear flow models are selected for their analysis in this study.

2.2 The WAsP model

Among the several linear flow models currently in use, in this study we analyse WAsP (Mortensen et al., 2007), developed by Risoe DTU, since is one of the most extensively used for micro-scale resource studies and much literature is available on its performances and limits (for a resume see Bowen and Mortensen, 2004). Relying on the linear flow theory (Jackson and Hunt, 1975), the WAsP software generalizes a meteorological data series at a reference site on a wind atlas of the region, which may then be used to estimate conditions at other predicted sites.

In general, the WAsP error in predicting mean wind speed largely depends on the reliability of input data and the degree to which it departs from the atmospheric and orographic conditions for which the model is designed. As regards atmospheric conditions, the measurement site and the predicted site must be subject to the same climate and prevailing weather conditions approach as a neutrally stratified atmosphere. A good indicator of the wind regimes' similarity in two sites is the wind speed correlation between prediction and measurements (Bowen and Mortensen, 2004). With respect to the orographic context, the fraction of the surrounding land that is above this critical slope (default 17°), defined as the ruggedness index (RIX), has been proposed as a coarse measure of the extent of flow separation (Mortensen et al., 1993), that is not simulated by WAsP. Zero RIX in one point means that the whole area around has gentle slope and good performances of the linear flow model are expected; the higher the RIX, the more the simulation moves away from the operational limits of the program (Bowen and Mortensen, 2004). A classification of topography based on RIX values into simple, medium and complex terrain is presented in Petersen et al. (1998).

Many studies have been carried in order to evaluate WAsP performances in complex terrain (Llombart et al. 2007, Berge et al. 2006, Moreno et al. 2003, Walmsley et al. 1990). However, all previous studies were focussed on evaluating performances for wind farm projects whose characteristics, as previously remarked, differ considerably from rural communities' off-grid electrification projects in developing countries. Good results of the model have been obtained in relatively flat terrain (Bowen and Mortensen, 2004) and in hills with maximum steepness of 25º till 5 km from the measurements (Sandstrom, 1994). Increasing distances could evidently play a significant role in reducing WAsP performances (Reed et al 2004, Bowen and Mortensen 2004, Berge et al 2006). Even if generally WAsP overestimates the speed-up when utilized outside its operational limits (Bowen and Mortensen 2004, Sandstrom 1994), in mountainous environment it has been found that if the predicted site is situated at a lower elevation than the meteorological station the wind speed is underestimated, and vice versa (Berge et al., 2006).

The topographic map used has a determining effect on the wind flow modelling in mountainous terrain. Two main parameters define its accuracy: the size and the height-contour interval. The map should extend to at least 5 km from any point of evaluation and the contour interval should be less than 20 m (Mortensen and Petersen, 1997) and up to 2 m in the area of study (Mortensen et al., 2008). The surface roughness expressed as the aerodynamic roughness length, i.e. the height where wind speed is zero (Stull, 1988), should also be defined in the whole map.

As resulting from literature analysis, even if many studies have been carried out in order to analyze WAsP performance in different contexts, most of them are focussed on grid-connected applications and wind farm areas. Therefore, conclusions of these studies could not be directly applied to rural electrification context, as none considers all the typical characteristics of an off-grid electrification project in mountainous environment. The aim of this study is the evaluation of WAsP model performance for those specific projects.

3. Data analysis

The accuracy of WAsP in mountainous context for rural electrification purpose is analyzed by applying the model for resource assessment in two communities (El Alumbre and Alto Peru) located in the Cajamarca region in the northern Andes of Peru, one of the areas with the greatest wind potential in the country (Meteosim, 2008). The general climate in the two communities is typical of the Andean region, where there are two main seasons: a rainy season with low winds between December and May, and a dry season with strong winds between June and November. The temperature is generally stable throughout the year, with mean daily temperatures between 10° and 15°. The presence of these 2 different wind regimes' along the year in the communities is verified by the collection of long term wind data (more than 1 year). As for stand-alone system design it is critical to evaluate the lowest resource period, wind data used for this study are collected during the rainy season between December and April.

3.1 Wind data and atmospheric condition analysis

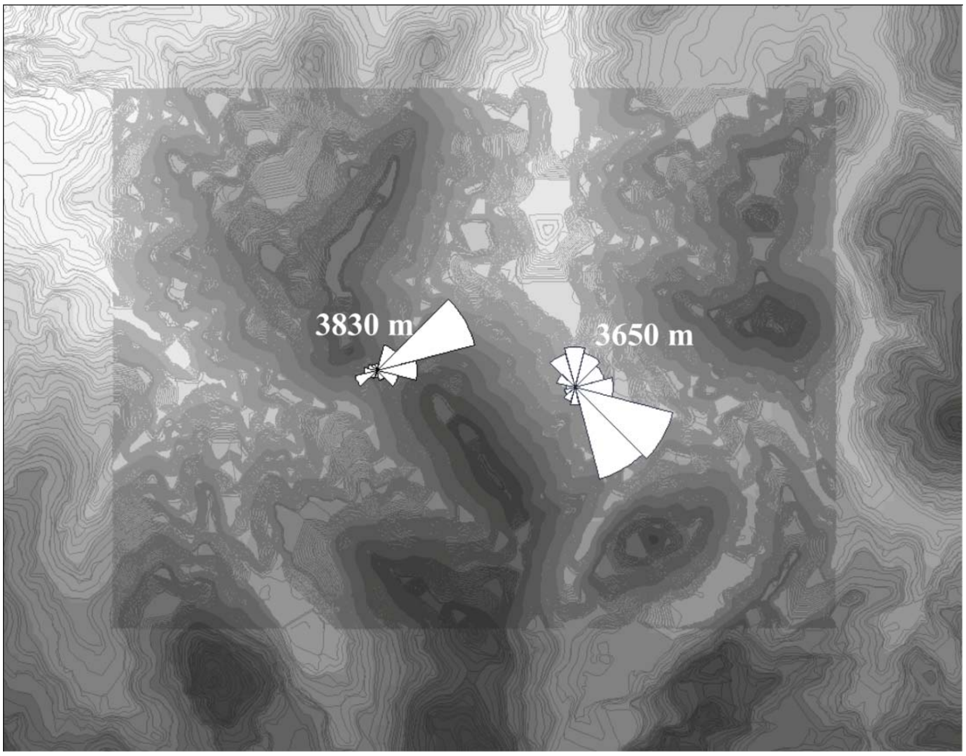
Two anemometers (NRG #40 three-cup anemometers and NRG #200P wind direction vanes) are installed in each community (El Alumbre and Alto Peru) in order to carry out a cross-validation process and evaluate the assessment uncertainty. The accuracy of those standard cup anemometers in those circumstances is around 0.1 m/s (Al-Abbadi and Rehman, 2009). The anemometers are located at 10 m above ground level (planned hub height of small turbines is 10 meters), mounted on a vertical boom above tower top in order to minimize influence of the tower on wind measurements. Data are logged every 3 seconds and 10-minute mean values are recorded and considered for this study, according to Ayotte et al. (2001). In El Alumbre, one anemometer is placed at an altitude of 3830 m (lat.: -6.882°, long.: -78.440°) and the other at 3650 m (lat.: -6.883°, long.: -78.422°). In Alto Peru, one anemometer is placed at an altitude of 3890 m (lat.: -6.903°, long.: -78.627°) and the other at 3570 m (lat.: -6.916°, long.: -78.647°). In general, all tower sites are open areas and the instrumentation is not obstructed by any building or elevated structure.

The data are simultaneously available from the two anemometers from 18th of December 2008 to 25th of March 2009 in El Alumbre and from 2nd of March to 4th of May 2009 in Alto Peru. Monthly divided data are utilized in the analyses; similar record lengths were used in Blashaval, and Askervein international experiments for validating micro-scale flow models (Walmsley et al. 1990, Taylor and Teunissen 1984).
In Figure 1 elevation maps with anemometer locations and wind roses are represented. In both communities main flow is highly affected by the meso-scale valley-mountain circulation pattern. This pattern is clearly evident in Alto Peru where slope direction is constant and no orographic element is present between the two anemometers; in both anemometers wind is mainly blowing from 2 opposite directions: upward anabatic flow (SW wind) during the day and down-hill katabatic flow (NE wind) during the night. In El Alumbre orographic situation is more complex (see Figure 2) and so is the mountain-valley circulation: the flow is turning following the orographic barrier present between the two anemometers (the dark area in the center of Figure 1a). The upper anemometer is located between two mountains picks: the flow is constrained by these barriers and is mainly an upward flux from NE. In the lower anemometer area (located in a valley) main flow is not upward neither downward, probably due to the higher steepness of the mountains in that

area (see Figure 2), and the flux is basically following the valley direction resulting in SE winds.

The correlation coefficients between anemometer wind speeds reflect the different situations of the 2 analyzed communities (Table 1): medium-high values are observed in Alto Peru (between 67 and 80%), while lower wind data correlations are encountered in El Alumbre (between 54 and 62%) where different main flow directions are observed.

The valley-mountain thermal circulation reflects a different atmospheric stability between valley and mountain zones; therefore non-uniform conditions and non-neutral stability are probably present during most of the day, thus highly departing from optimal atmospheric situation assumed by WAsP wind flow simulation. Therefore, even if correlation coefficients are acceptable, the atmospheric conditions in both communities are bordering WAsP operational limits and good model performance are not ensured by literature, as previously defined, and should therefore be evaluated.



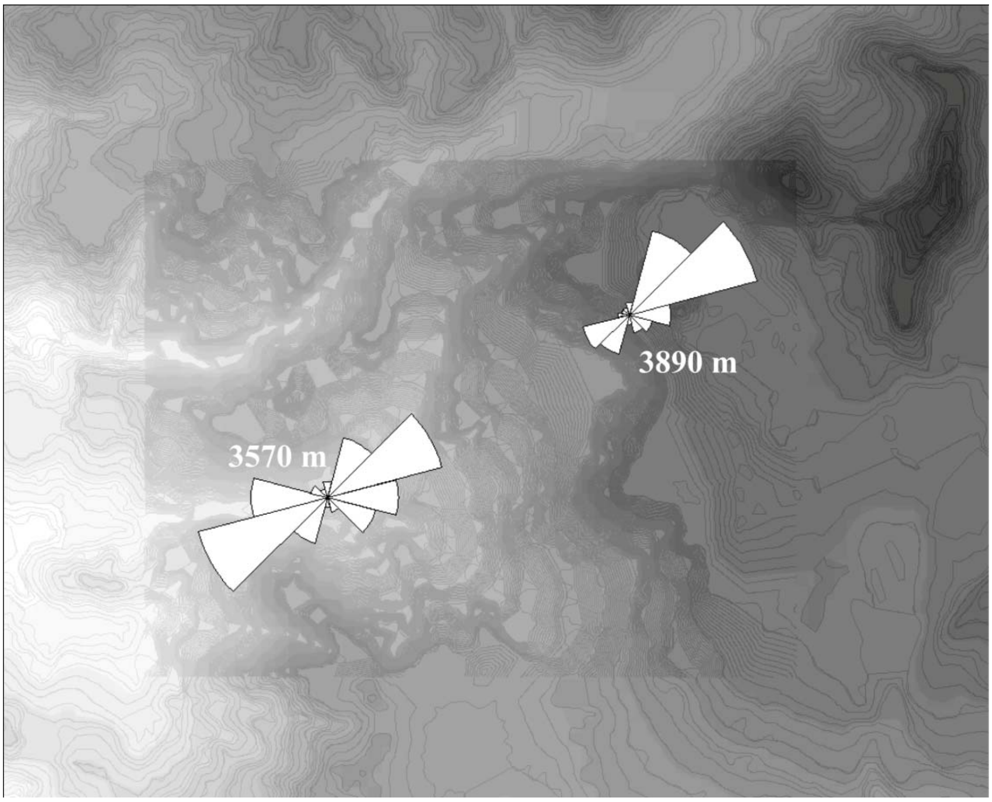


Figure 1 – Topographic maps of El Alumbre (Figure 1a) and Alto Peru (Figure 1b) with anemometers location, height and wind roses for March 2009 wind data. Darker colours mean higher terrain elevation

Monthly average wind speeds are displayed in Table 1. As expected, higher mean wind speeds are registered by the anemometers located close to the hilltop (higher part) due to topographic speed-up effect.

Table 1. Mean monthly wind speeds in m/s and monthly correlation coefficients between 10-minutes mean wind data of the two anemometers in El Alumbre and Alto Peru

	El Alumbre			Alto Peru		
	Higher part	*Lower part*	*Correlation coefficient*	*Higher part*	*Lower part*	*Correlation coefficient*
December 2008	2.7	2.5	56%			
January 2009	3.0	2.6	54%			
February 2009	3.4	2.6	62%			
March 2009	2.9	2.5	59%	3.1	2.4	67%
April 2009				4.0	3.4	80%

3.2 Input Maps

Besides wind data, the input data required for calculations are mainly the topographic and roughness maps. Community maps (with a 25 m contour interval) are purchased in order to cover a minimum area of 5 km around each anemometer, as defined by the WAsP literature (Mortensen and Petersen, 1997).

However, literature advices the use of contour interval lower than 20 m (Mortensen and Petersen, 1997), and till 2 m interval in the area closest to the anemometers (Mortensen et al., 2008) therefore a treatment of the purchased maps is carried out: height contours are interpolated in order to obtain the required detail. Lower contour-height intervals are obtained utilizing specific software that implements a Triangulated Irregular Network (TIN) for grid interpolation. In both communities surface is constituted mainly of pasture with some isolated tree, therefore a uniform roughness in the whole area is considered; in Alto Peru a few lagoons are presents close to the upper part of the community and are modelled through satellite images with zero roughness. In section 4.1 sensitivity analyses of the topographic map (detail and contour resolution) and roughness value on WAsP performance are described and final characteristics of the input maps utilized are defined.

3.3 Topographic indicators analysis

As defined in the WAsP description, besides atmospheric conditions and input data quality, some topographical parameters indicate the degree to which the real conditions of the study site differ from the optimum conditions for the WAsP operating envelope and determine the reliability of the assessment. Two central factors can be easily evaluated: the distance between anemometers and the RIX parameter of the area, that is automatically calculated by the model.

As WAsP simulations are carried out considering the data of only one anemometer as input (a characteristic of the model), wind flow modelling is expected to worsen as the distance from the anemometer increases (Reed et al. 2004, Ayotte et al. 2001, Berge et al. 2006). The RIX value, described in section 2.2, can indicate the flow separation extension and the extent to which the terrain violates the requirement of WAsP (the ideal value is zero RIX). Figure 2 shows the RIX values in the two areas of study; dark areas correspond to a RIX greater than 10%. In the Alto Peru community RIX values are lower than 10% and the RIX between the two anemometers ranges between 6% and 9%. As observed in section 3.1, the community of El Alumbre is located in a topographically more complex area with slightly higher values of RIX (up to 17%). However most of El Alumbre area has lower RIX values, mainly varying between 8% and 13% (anemometers RIX). Both sites could be considered as medium complex terrain, as most of the area has RIX values lower or equal than 10% (Petersen et al., 1998).

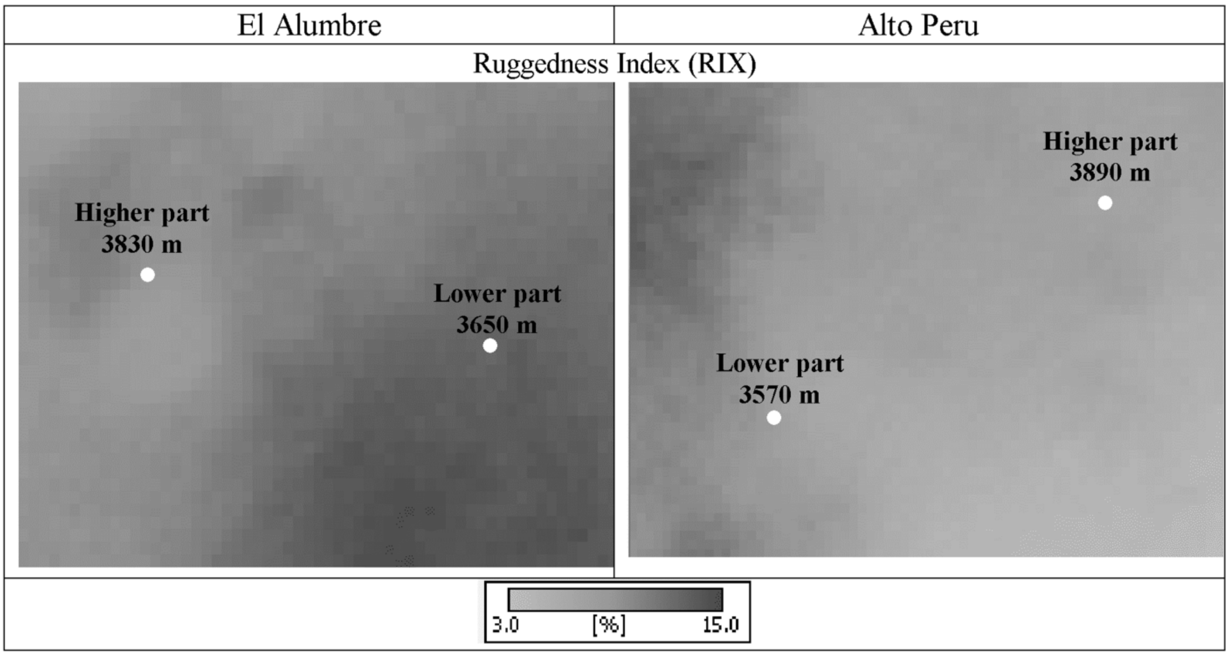


Fig. 2. RIX values in El Alumbre (left) and Alto Peru (right). Anemometer locations are visualized as white circles

Table 2 summarizes the values of these local factors in the communities of El Alumbre and Alto Peru. The RIX is higher in the El Alumbre area, while the distance between anemometers is higher in Alto Peru. As for atmospheric condition, topographic steepness (RIX values) differs from the optimal settings for the proper functioning of WAsP and an aim of this study is to check whether the results can be considered reliable under these conditions for the distances involved.

Table 2. Influential local factors in the accuracy of WAsP predictions

	El Alumbre	Alto Peru
Distance	1950 m	2650 m
Upper anemometer RIX	8%	9%
Lower anemometer RIX	13%	6%
RIX range	7–13%	6–10%

4. Results and discussion

In this section, results of the model simulation are reported and discussed. Since wind flow modelling accuracy is highly dependent on the accuracy of the input data, sensitivity analyses are firstly carried out to evaluate the factors that are required to achieve reliable simulations. WAsP prediction errors are analysed and discussed in section 4.2 and, finally, resulting wind resource maps are described in section 4.3.

In mountainous areas that are outside model operational limits, the use of WAsP considering the anemometer located in the lower part of the analyzed area as reference site is generally discouraged as considerable overestimations are expected, according to

Sandstrom (1994), Bowen and Mortensen (2004) and Berge et al. (2006). Therefore, in the following sections, prediction errors are always obtained considering wind data from the anemometer in the higher part as input data (reference site) predicting wind velocity in the lower part (predicted site), see Figure 1. Prediction errors are calculated as the difference between the mean wind speed model prediction at the predicted site (lower part anemometer) and the wind data measured by the anemometer at that location. Errors are reported as percentages with respect to the measured wind speed.

4.1 Sensitivity analysis of roughness and topographic maps

This section describes the treatment of the roughness and topographic maps and the importance of each input data in the accuracy of predictions.

4.1.1 Roughness map and obstacles

The surface in both community areas is constituted mainly of pasture with little vegetation cover. For this kind of land, the WAsP manual recommends a roughness length value of 0.03 m (Mortensen et al., 2007). Different roughness configurations are studied in order to analyze how these variations and the simulation of higher trees density areas (with higher roughness) affect the flow modelling. By varying the roughness length between 0.02 and 0.04 m, changes in the predictions prove to be relatively limited and it is found that the simulation of the forests present in the area doesn’t affect the results, probably due to the small size of forest areas and their distance from anemometers. Therefore, a constant roughness length of 0.03 m is considered. In the area of Alto Peru, existing lagoons are modelled through satellite images with zero roughness.

Obstacles affect the main flow up to three times the height of the obstacle (Mortensen et al., 2007). All the houses in the El Alumbre and Alto Peru communities are lower than 3.5 m, so in theory the presence of obstacles does not have a significant effect on the flow simulation at the height of the anemometer (10 m). Anyhow, in order to verify this assumption in this specific condition, in which wind flow is modelled at a small height, differences of including or not the obstacles in the simulation are analyzed. In both communities, it results that prediction differences obtained with or without obstacle modelling are lower than 1% in mean wind speed, so their influence could be considered negligible and no obstacles need to be simulated.

4.1.2 Topographic map

In order to improve topographic detail, some treatment of the maps is required. Firstly, mountain peaks are digitalized and the topography around each anemometer is defined as precisely as possible. The presence of plain elements like lakes or football fields may be very useful in this process. Table 3 shows the prediction errors, i.e. the difference between the predicted wind speed and the measured wind speed at the lower part anemometer, obtained with or without topographic map redefinition. The prediction errors shown are the average errors of the monthly comparisons obtained in both communities. As shown, prediction accuracy increases considerably when the surrounding topography is redefined with greater detail. This effect is more important in El Alumbre, where the anemometer in the higher part is located very close to a football field.

Table 3. Prediction errors obtained with WAsP considering maps with and without topographic redefinitions.

	Mean prediction error [%]
Without topographic redefinition	**12.3**
With topographic redefinition	**7.8**

A sensitivity analysis on height contour interval shows that interpolating curves obtaining lower contour-height intervals strongly increase the accuracy of the WAsP model. Table 4 compares prediction errors obtained using contour intervals of 25 m, 10 m and 2 m. The prediction errors shown are the average errors of the monthly comparisons obtained in both communities.

Table 4. Prediction errors obtained with WAsP considering maps with different height-contour intervals.

Height-contour interval	Mean prediction error [%]
25 m	**12.5**
10 m	**8.9**
2 m	**7.8**

It should be noted that the map size is limited by the WAsP program (1,000,000 points) and therefore contours could not be interpolated to a 2-m interval on the whole map. Different analyses revealed that an interpolation at 10 m within 3 km from the anemometers and at 2 m within 1 km from the anemometers is sufficient. Prediction changes using more detailed maps are negligible. Final topographic maps utilized for calculation have decreasing height-contour intervals as approaching anemometer location, as shown in Figure 1 (higher height-contour intervals are present at the borders of the map). The final map (Figure 1) covers an area of at least 5 km from the studied sites as recommended by Mortensen and Petersen (1997).

4.2 Prediction errors

This section analyzes the results obtained with WAsP. As defined, wind data are divided by months and comparisons are made according to monthly averages. Considered input data are those identified by the sensitivity analyses described in section 4.1: no obstacles representation, uniform terrain roughness of 0.03 m in both communities with the definition of lagoons area with 0 roughness, topographic map covering the area up to 5 km around both anemometer with an increasing resolution (25 m contour interval at the border of the map, an interpolation at 10 m contour interval within 3 km and at 2 m within 1 km from the anemometers). Table 5 contains a summary of the monthly wind speed averages, predictions and errors obtained by WAsP.

Table 5. Prediction errors obtained by WAsP considering the anemometer in the higher part as reference input data (reference site) predicting mean wind speed at the lower anemometer location (predicted site).

Community	*Month*	*Anemometer data*		*WAsP*	
		Reference site [m/s]	*Predicted site [m/s]*	*Prediction [m/s]*	*Error [%]*
El Alumbre	December 2008	2.7	2.5	2.6	6.0
	January 2009	3.0	2.6	2.5	-6.4
	February 2009	3.4	2.6	2.5	-4.6
	March 2009	2.9	2.5	2.4	-4.7
		Mean error (absolute value)			**5.5**
Alto Peru	March 2009	3.1	2.4	2.3	-6.6
	April 2009	4.0	3.4	2.9	-13.7
		Mean error (absolute value)			**10.1**

Estimation errors in the lower part are very low in El Alumbre (from 4.5% to 6.5%). It should be noted that WAsP underestimate the resource in all the analyzed months, as obtained by (Berge et al., 2006), with an exception in December 2008. Slightly higher estimation errors are encountered in Alto Peru (up to 13.7%), where in all the simulated months results confirm the general tendency of the model to underestimate the resource. The average mean error in absolute value is 5.5% in El Alumbre and 10.1% in Alto Peru. With a single exception (April 2009 in Alto Peru), it should be noted that the errors are always lower than 7% in both communities. Hence, predictions can be considered highly accurate, in particular considering that the absolute error already assumed of 0.1 m/s in wind measurements (Rodriguez et al 2003, Al-Abbadi and Rehman 2009) means a relative error of up to 5% for low wind speeds between 2 and 3 m/s.

4.3 Wind resource maps

As resulted from the analysis of the model performance (section 4.2), wind resource maps obtained can be considered highly accurate and, thus, can be used as a reliable data for the design optimization of wind electrification projects. In particular, the wind resource assessment procedure analysed and proposed in this study was used in the design of the electrification project of Alto Peru that was promoted and implemented by the NGOs Practical Action (Peru), Engineers without Borders (Spain) and Green Empowerment (USA) in 2009.

Alto Peru has around 90 houses scattered in an area of 20 km^2 (Figure 3). The detailed wind resource map obtained in Alto Peru (Figure 3) shows that wind resource in the area is very variable: although the wind resource is high in some parts, especially around the upper anemometer, the wind resource of the rest of the community is low to moderate. Thus, according the results of the wind resource assessment, the promoters of the electrification project decided to use wind systems to electrify the houses close to the upper anemometer (Figure 3) but to study other technological options for the rest of the households.

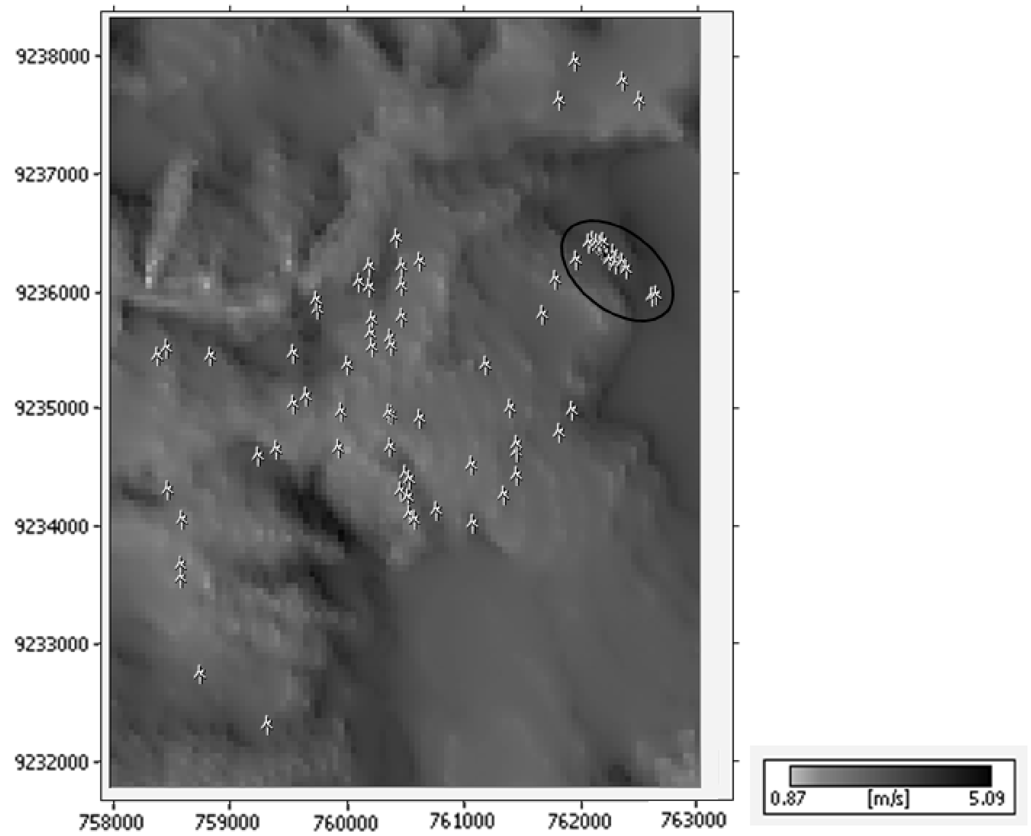


Figure 3 – Mean wind speed in the area of Alto Peru with houses location. The houses inside the dark cicle are those that have been electrified by wind systems.

5. Conclusions

The objectives of this study are the analysis of the performance of micro-scale models for wind resource assessment when applying wind flow models in the typical context of mountainous off-grid rural electrification projects in developing countries. This type of applications is out of the operational limits of these models and, thus, a procedure to pre process the topographical data and an analysis of the evaluation accuracy is needed to allow its reliable use in these projects. The software considered in this work is WAsP, a widely use commercial linear flow model. Its performance are analysed by applying the model in two Peruvian mountainous communities.

The analysis of the performance of the model shows that the topographical map has a significant influence on the model prediction accuracy: topographic details should be defined with utmost accuracy, in particular around the anemometers, and height-contour lines must be interpolated in order to reach the required detail. Although a highly detailed roughness map is not needed, representing significantly different areas, for instance lagoons with null roughness, is recommended. Community houses, which are much lower than turbine, have a negligible effect on the main flow estimations at turbine hub height and therefore don't need to be represented. Although WAsP model is used outside its operational limits and considering limited data available, with this procedure, the results show good model performance and accurate resource evaluation for the distances involved.

The model analysed and procedure for input data pre-process can be then considered suitable for wind potential studies for similar projects and, thus, the results of this study clearly recommend their use. In particular, wind resource assessment partly described in this study was utilized in the definition of Alto Peru electrification design. The application of a micro-scale model in estimating the wind resource in rural communities will help the promoters in optimizing the design of the projects, reduce the uncertainty of supply problems related to wind technology and improve the effectiveness and impact of off-grid renewable energy projects.

Acknowledgements

This paper was supported by the Spanish MICINN project ENE2010-15509 and co-financed by FEDER, by the Catalan Agency for Development Cooperation and by the Centre for Development Cooperation of the Technical University of Catalonia (UPC). Matteo Ranaboldo kindly acknowledges the Spanish Ministry of Education for the FPU scholarship. The authors are very grateful for all the assistance and support provided by Practical Action from Peru, Engineering Without Borders – Catalonia from Spain and Green Empowerment.

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Renewable energy projects to electrify rural communities in Cape Verde

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Article published as [Ranaboldo M, Domenech B, Vilar D, Ferrer-Martí L, Pastor R, García-Villoria A. Renewable energy projects to electrify rural communities in Cape Verde. Applied Energy 2014; 118: 280–91] © [copyright Elsevier]

Abstract

Even though Cape Verde has high wind and solar energy resources, the conventional strategy for increasing access to electricity in isolated rural areas is by centralized microgrids with diesel generators. In this study, the design of 2 off-grid electrification projects based on hybrid wind-photovoltaic systems in Cape Verde is developed and analyzed. The design considers some significant novelty features in comparison with previous studies. First a detailed wind resource assessment is carried out combining meso-scale wind climate data and a specialized micro-scale wind flow model. Then a mathematical model is used for the design of off-grid projects considering a combination of individual systems and microgrids. In this study, locations far from the demand points are also considered as possible generation points. Various design configurations are analyzed and compared. The proposed configurations exploit the highest wind potential areas and are economically beneficial in comparison with diesel generator systems.

1. Introduction

Cape Verde is an archipelago located in the Atlantic Ocean with a total population of half a million people. Its electrical energy production relies largely on diesel thermal plants [1] and is highly dependent on (totally imported) fuel. Cape Verde electric power price is therefore highly affected by fuel price fluctuation and is currently around 0.40$/kWh, among the most expensive in Africa [1]. The electrification rate was around 70% in 2010, relatively high in comparison with other countries of its region [1]. During the last decades, the conventional strategy for increasing access to electricity in rural areas of Cape Verde has been to extend the national electricity grid or by autonomous microgrids with diesel

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generators [2]. Due to the complex geography and dispersed nature of villages in mayor islands of Cape Verde, the expansion of the electricity grid can only reach a limited number of people. Furthermore, during the last decade connections to the grid increased rapidly while installed capacity remained stable; as a result of this tight demand-supply balance, the incidence of blackouts more than tripled and became longer in duration [1]. On the other side, local microgrids powered by small diesel generators, which supply electricity for a significant proportion of isolated communities or municipalities [2], have some clear disadvantages and limitations, such as the high and variable cost of the fuel, the requirement of a continuous supply and the inherent carbon dioxide and other polluting emission.

Under these circumstances, stand-alone electrification systems that use renewable energy sources are a suitable alternative to provide electricity to isolated communities in a reliable and pollution-free manner [3]. Moreover, one of their main advantages is that they use local resources and do not depend on external sources, which can promote the long-term sustainability of the projects. Specifically, Photo-Voltaic (PV) systems have already been widely used in the last decades, while wind systems, less used, are receiving increasing attention for off-grid generation [4]. In windy areas, the ratio investment / produced energy can make wind energy a very favorable technology, especially when demand increases and more powerful wind turbines are used (for instance, when supplying to groups of households with microgrids [5]). In this context, hybrid systems that combine wind and solar energy sources are a promising generation option [4].

Most stand-alone electrification projects based on wind and solar energies consist of installing individual systems [6, 7]; that means each consumption point (for example, households, health centers or schools) has its own generators. As an alternative, microgrids can be used: a generation point produces energy for a number of consumption points. It is generally known that microgrids have several advantages in comparison with individual systems [8]. First, when using those configurations, user energy availability does not depend on the resource in its location. Second, equity between user consumptions is improved by relying on the same generators, i.e. all connected users share the same generated energy. Third, costs can be reduced by economies of scale (when installing more powerful generators a lower ratio between the generators cost and the energy produced could be reached). Finally, a greater flexibility in consumption is permitted: consumption can punctually be increased due to special days, admission of new users or the development of productive activities, i.e. the implementation of local businesses could involve higher energy requirements. Despite the advantages of microgrids, a too large extension may cause problems due to the increasing cable cost [9]. Thus, the design of stand-alone renewable energy projects is highly complex as it requires the characterization of both energy resources in every point of the community and aims to find a good compromise between microgrids' extension and individual electrification [5, 10].

Various papers study the design of autonomous electrification systems at village level in developing countries through the use of renewable energies [4, 10, 11, 12, 13, 14]. In this context, most studies basically focus on defining the best combination of renewable generation sources without considering energy resource spatial variations [11, 12, 13, 14]. HOMER developed by NREL is the most widely used decision aid tool, which simulates and compares lifetime costs of different alternatives of electrification [13, 14]. However, recent rural electrification projects confirmed that significant wind resource differences could be present between houses of a community in hilly terrain [15]. In these cases, a single wind resource data, as considered by e.g [2, 11, 12, 13, 14], is not representative of the whole area and detailed resource studies are required for defining generators locations. Moreover very few studies focus on the design of microgrids and the definition of the system, but with some limitations [16, 17]. ViPOR [17] uses the output from HOMER to design a distribution system combining microgrids and individual systems. However, this tool limits the possible generation points and the number of microgrids; furthermore it does not consider voltage drops in microgrid design. To overcome these limitations, a mixed integer linear programming (MILP) model was developed for the design of wind electrification systems, considering the detail of wind resource, the demand of each consumption point, the storage in batteries and the distribution through microgrids [5]. Recently, solar energy has been included in the previous model, to obtain the optimal combination of wind-PV technologies for every selected generation point [10].

Cape Verde is located in a sub-tropical region and receives a significant solar radiation during the whole year. Furthermore, tropical trade winds are well developed over most of Cape Verde islands and exposed sites have a large wind resource [18, 19]. In the last years different studies have been carried out showing the reliability of renewable energy projects and proposing an increase of the penetration of renewable energy sources in Cape Verde [2, 19, 20, 21]. In particular, a recent study [2] focusing on the communities of Figueiras and Ribeira Alta (in the island of Santo Antão), proposes the replacement of the current diesel systems with hybrid systems combining diesel, wind and solar energies. However, in that study the wind energy production was roughly estimated by wind data of a far off meteorological station and was considered uniform around the community area. Therefore, the design of the projects was just preliminary and mainly focused on the economical comparison with current diesel systems.

In this context, this paper develops accurate studies to design off-grid rural electrification projects with wind and solar energies in 3 communities of Cape Verde: Figueiras and Ribeira Alta in Santo Antão Island and Achada Leite (currently not electrified) in Santiago Island. The design considers some novelty features in comparison with previous studies and is composed by two main steps. Firstly, a high resolution wind resource assessment is realized combining generalized wind climate data and a specific wind flow model that takes into account real topographical wind speed changes to detect micro-scale wind resource variations [15]. Then, the previously mentioned MILP model [10] is applied. The model optimizes the technical design of the electrification system minimizing the cost and specifying the amount and size of the equipment to be installed. Moreover, in this study, locations with a good resource far from the demand points, i.e users, are considered as possible generation points, while generally generators are forced to be installed close to the users [5, 10].

The final proposed electrification systems are totally based on renewable energies and take advantage of best resource areas. Besides avoiding greenhouse gases' emissions and reducing the external dependency on fuel importations, they result to be economically beneficial in comparison with diesel generator systems and even with the hybrid wind-solar-diesel system proposed in ref. [2]. The systems designed in this study can be used as pilot projects in order to facilitate governmental investments on renewable energy and spread their utilization in rural electrification projects in Cape Verde.

The rest of the paper is organized as follows. First the studied communities are described (Section 2) and the micro-scale wind resource assessments are carried out (Section 3); in Section 4 the optimization model for off-grid electrification design is summarized. Various design configurations for the electrification of the studied communities are analyzed in Section 5. In Section 6 an economical and environmental analysis of the proposed solutions in comparison with diesel generation option is carried out. Finally (Section 7) the conclusions of the study are exposed.

2. Communities descriptions and previous studies

Cape Verde is a 10 islands archipelago located in the Atlantic Ocean 500 km off the West African coastline, covering an area between longitude 22-26º W and latitude 14-18º N (Fig. 1). The analyzed communities are Figueiras and Ribeira Alta in Santo Antão Island, and Achada Leite in Santiago Island. Their location is shown in Fig. 2. The first two communities (Figueiras and Ribeira Alta) are studied together due to their proximity. From now on, the 2 studied projects will be referred to as "Santo Antão project" and "Santiago project".

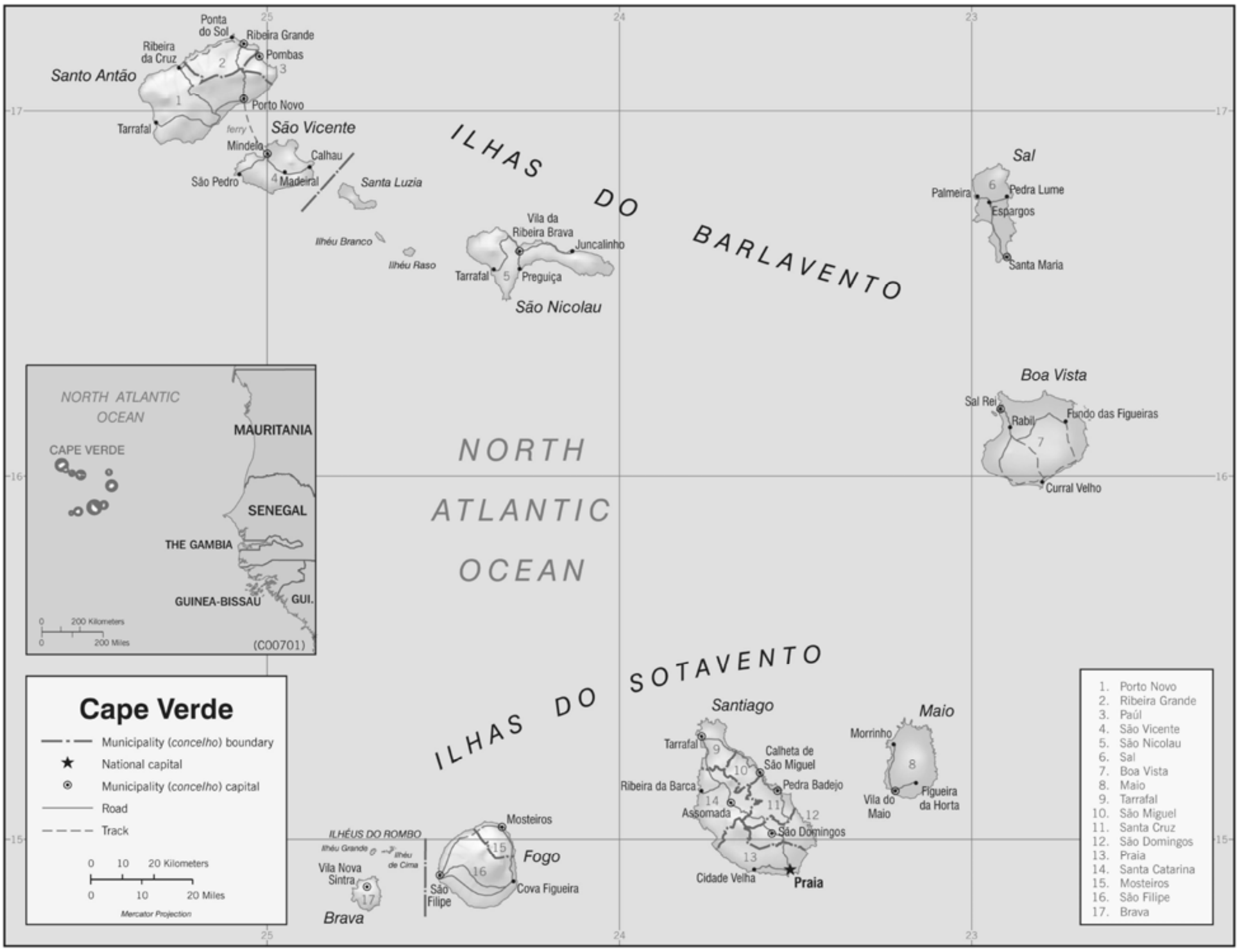

Fig.1. Cape Verde map [21]

The solar resource of Cape Verde is high and rather uniform with a mean global irradiance generally varying between 5 and 7 kWh/(m2·day) along the year, according to NASA climate database with a resolution of 0.5º (around 50 km) [22]. As spatial variation of global irradiance is lower than 5% in areas of less than 30x30 km even in mountainous areas [23], the solar resource is assumed to be uniform in the studied areas. In order to carry out a conservative analysis, the lowest resource month in Cape Verde is considered in this study, i.e. December with a mean global irradiance of 4.8 kWh/(m2·day) as by ref. [22].

The wind climate of the country is the typical of sub-tropical region with trade winds prevailing: in most sites dominant wind direction is from the northeast during the whole year. A meso-scale wind resource map of the country is available [18], obtained using the KAMM/WAsP numerical wind-atlas method [24]. The resulting resource map (Fig. 2) gives information about mean wind speed and power density at 50 m with a grid spacing of 0.05º of latitude/longitude, i.e. a modelling resolution of around 2.5 km. Outputs of the numerical wind atlas have been verified in different locations in Cape Verde and show good results in comparison with in-situ measurements [18]. Fig. 2 shows the meso-scale wind resource maps in the islands of Santo Antão and Santiago, where the 3 analyzed communities are located. Wind resource in the areas of these communities is good with mean wind speeds at 50 m between 5 and 7 m/s. The seasonal wind speed variation along the year is around ±10% with respect to the annual mean value with higher values in winter and lower in summer [22, 25]. As a high variability of the wind resource is expected in hilly terrain even at a micro-scale [15], a detailed assessment is carried out in Section 3.

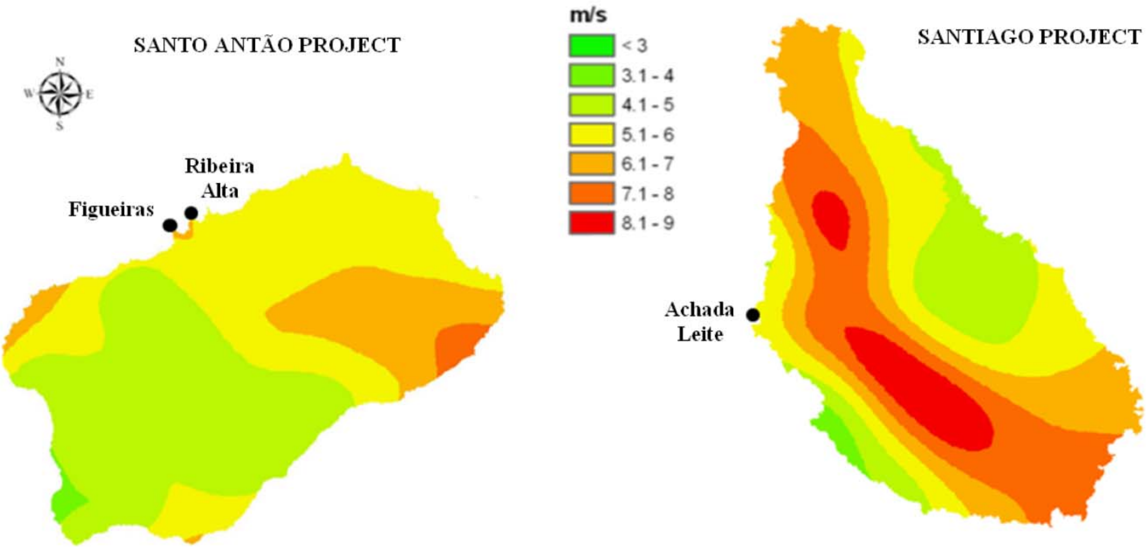

Fig.2. Mean wind speed at 50 m in Santo Antão and Santiago Islands [18]. Black point indicates studied communities' locations

2.1. Santo Antão project

Figueiras and Ribeira Alta communities are located in two adjacent valleys on the northern coast of Santo Antão. The distance between the 2 communities is around 1 km. The communities of Figueiras and Ribeira Alta are composed of 122 houses (450 inhabitants) and 47 houses (180 inhabitants) respectively. The total area covered by the project is around 16 km^2. In each community there are 2 schools and one health center. The two communities are currently electrified by two different microgrids (one for each community) based on diesel generator systems which supply energy to all users (houses and public buildings).

A recent study of the Global Environmental Facility (GEF) [2] developed a costs' comparison between the current diesel system and a proposed hybrid system based on a combination of diesel, wind and solar energies. The renewable energy contribution in that hybrid system was around 90% of which more than 70% was from wind power in both communities. For this purpose an accurate analysis of users' future energy requirements and of initial and annual costs of the hybrid system components was carried out [2]. However, the wind resource assessment was based on a manual extrapolation, by means of an empirical coefficient, of wind data measured in a meteorological station located in another island (São Vicente Island) more than 50 km away from analyzed communities. The uncertainty of this assumption is high as the wind climates of the 2 islands are different, in this sense the selection of the empirical coefficient is complex and its incorrect estimation could lead to significant errors. Furthermore, the definition of wind turbines positions and electric wires design were not analyzed by [2] as the resource was considered uniform in the community. Therefore, the described study [2] could be considered as a first approximation to the design of the project. In this study we aim to realize a detailed analysis and develop a real project considering micro-scale wind resource variation and microgrids design.

2.2. Santiago project

Achada Leite is a rural community located on the western coast of Santiago Island, the most populated island of Cape Verde. The community is composed by 42 houses and a school with a total population of around 90 inhabitants, distributed in an area of 0.3 km^2. Nowadays, no electrification systems are present; the closest connection to national grid is at around 3 km (straight line distance) in mountainous terrain. To our knowledge, no previous study on the design of an Achada Leite electrification project has been carried out until this document was finished. Thus, no data in terms of energy requirements and equipment costs are available. As the 3 studied communities have similar electricity requirements, the same input data (in terms of per house energy and power demands) as for Figueiras and Ribeira Alta communities [2] will be used for Achada Leite design analysis.

3. Micro-scale wind resource assessment

In the areas of the studied communities no wind measurements are available; therefore wind resource is estimated from the numerical wind atlas [18]. In order to evaluate the wind resource with higher detail a micro-scale analysis is carried out with WAsP software [26], a wind flow model, which assumes that the slope of the surface is small enough to neglect flow separation and linearize flow equations. It permits calculating wind climate data of every point of a certain area considering topography and roughness changes. WAsP software has been and is currently widely used for evaluating wind resource differences at a small scale (in areas of less than 10x10 km^2) in order to site turbines and its operational limits are well known [27]. An important parameter to ensure WAsP performance is the topographical map quality. WAsP literature recommends that the map should extend to at least 5 km from any point of evaluation in the predominant wind direction and the height contour interval should be less than 20 m [26] with lower interval closer to the evaluated area. In both islands the available map is sufficiently detailed with a height contour interval of 5 m. Regarding the orographic context, a central parameter for defining the operational limits of the model is the ruggedness index (RIX) that indicates the fraction of the surrounding land above a critical slope (default 17°) [27]. It was verified that, with good input data and involved distance of few kilometers, WAsP estimation error is limited for rural communities' studies in medium complex terrain, i.e. RIX values around 10% in most of the area [15]. In both studied projects RIX values are below 10% in the prevailing wind direction (N – NE), therefore WAsP modelling is expected to be reliable.

The wind resource is modeled at 20 m a.g.l. which is the proposed hub height of wind turbines (with nominal power between 600 to 7500 W). Different assessments were carried out using the 4 closest grid points of the meso-scale numerical wind atlas [18] surrounding the studied areas. Then, as a conservative assumption, the meso-scale wind atlas which leads to the lowest wind resource in the analyzed areas is considered. Finally, as annual resource variation along the year is around ±10% [22], a decrease of 10% on the mean wind speed is applied to wind climate average values [18] in order to consider less windy season.

3.1 Santo Antão project

As shown in the topographical map of Figure 3 where darker colours indicate higher heights, Figueiras and Ribeira Alta are located in two valleys with areas of abrupt terrain in Santo Antão Island. The installation of wind turbines close to the houses is not adequate due to the presence of turbulence induced by slope steepness. As main wind has a basically constant direction from North-East (trade winds), coastal areas are well exposed to main flow. While in Ribeira Alta area the coast line is composed by hardly accessible valleys, in the coastal surrounding of Figueiras community (around 1 km North-West) a smooth hill is present that could be a promising location for wind turbines installation. Therefore, a detailed wind resource assessment is carried out in this area (indicated as a black square in Fig. 3). As confirmed by site visit, the selected area is directly exposed to trade winds blowing from North-East and is well connected to the community by a constructed path that reaches the football field located on the same hill. Due to the limited number of map points accepted by WAsP software, a contour interval of 20 m is used in the areas far from the hill in order to fulfill the recommended map extension; in the surrounding of the studied area, a 5 m contour interval is used. As terrain is basically composed by grass with few trees, a roughness length of 0.03 m is given to land areas and a null roughness length is assigned to the sea [26].

As previously stated, due to their proximity and the presence of a single area for wind generation, the design of Figueiras and Ribeira Alta systems are studied together in a single project (the "Santo Antão project"). The area of the project is shown in Fig. 3 (right) together with the wind resource map of the smooth hill close to Figueiras community (left). A good wind resource is present in the site with a mean wind speed of more than 6 m/s at 20 m a.g.l. in best exposed locations.

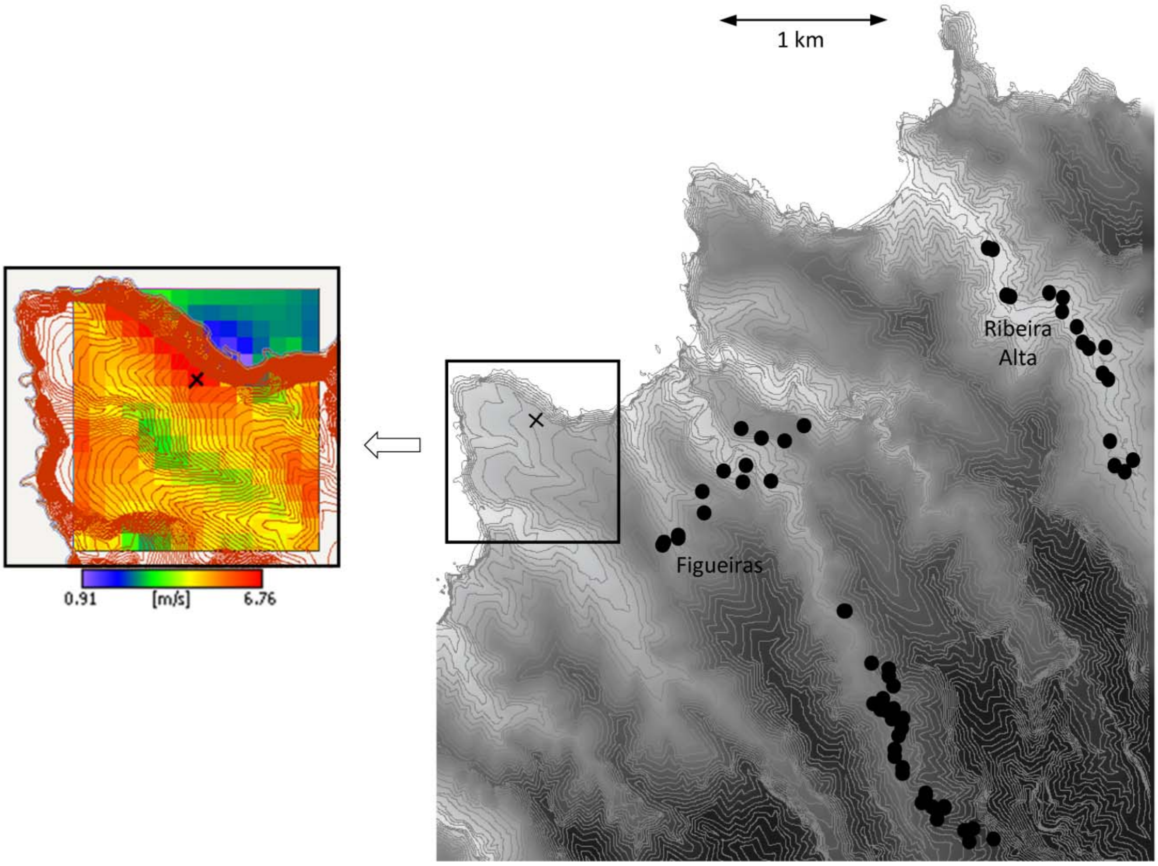

Fig.3. Santo Antão project topography (right) and mean wind speed at 20 m a.g.l. in the smooth hill close to Figueiras (left). Users' positions are shown by black circles. The "X" indicates the selected wind generation point

3.2 Santiago project

Achada Leite is a coastal community located in smooth hilly terrain area in Santiago Island. The wind resource is evaluated for an entire area within a radius of around 1 km around the houses. In this case, the 5 m contour interval map is used in the whole area without exceeding the maximum number of points accepted by WAsP. A roughness length of 0.03 m is given to most land areas, as terrain is composed by grass with few trees, while a palm forest located in the center of the community is modeled with a higher roughness of 0.8 m and a null roughness length is assigned to the sea [26].

Resulting wind resource map (Fig. 4) shows a high variability of resource in the analyzed area. Project area (indicated by a black square in Fig. 4) has a pretty low wind resource with mean wind speeds ranging from 2 m/s (in the palm forest area) to 3.5 m/s (at houses located at a higher elevation) at 20 m a.g.l. Meanwhile, a higher wind resource area is located in the north of the community where a promontory is located close to the sea (indicated by a black ellipse in Fig. 4), therefore exploiting the trade winds blowing from north and north-east; mean wind speeds up to 6.5 m/s are present in this area.

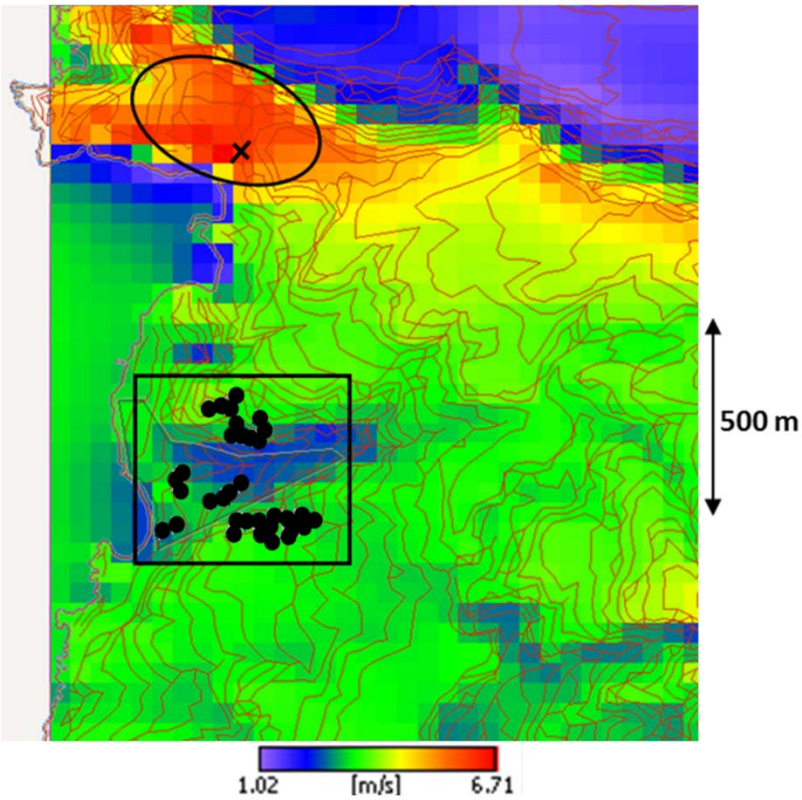

Fig.4. Mean wind speed at 20 m a.g.l. in Santiago project area. Community houses and school positions are shown by black circles. The “X” indicates the selected wind generation point

4. Rural electrification systems design

In this Section stand-alone electrification systems using wind-PV generation technologies and microgrid and/or individual distribution schemes are firstly described (Sub-section 4.1). Then the optimization model for the design of the described electrification systems is outlined (Sub-section 4.2) and finally input data used for the design are reported (Sub-section 4.3).

4.1. Technical description

The scheme of a stand-alone rural electrification system based on wind-PV energies with microgrid distribution is shown in Fig. 5.

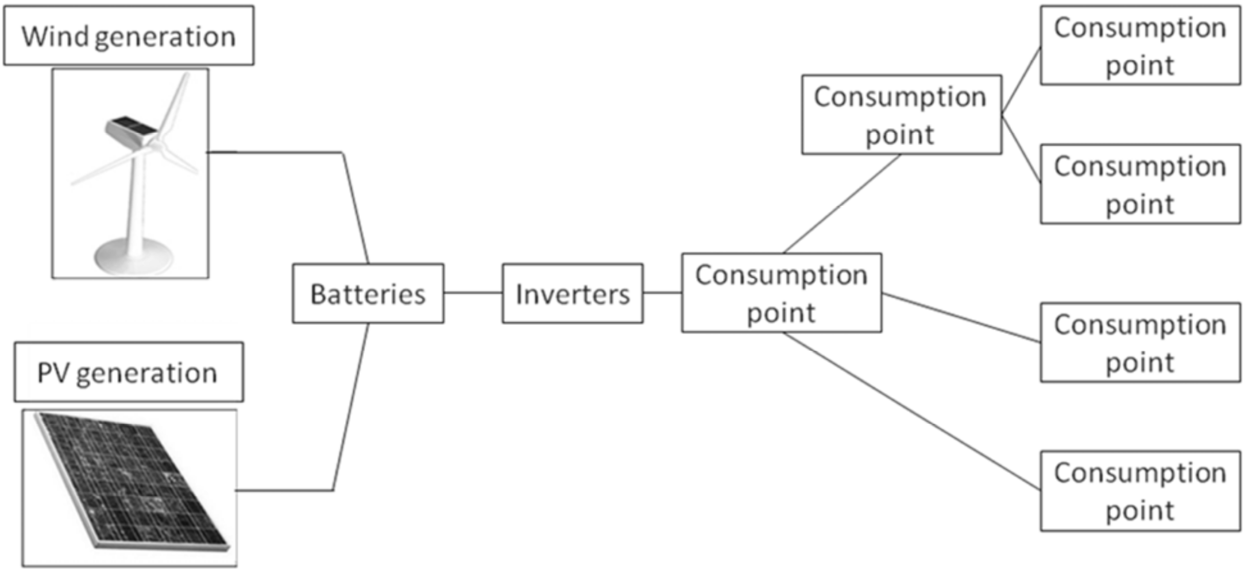

Fig.5. Scheme of the elements involved in a hybrid wind-PV electrification system [10]

Characteristics and functions of each element are next summarized [10]:

- Wind generation includes wind turbines and controllers. Wind turbines transform kinetic energy from the wind into electrical energy. The electricity is generated in alternating current (AC). Wind controllers transform AC into direct current (DC) and protect batteries from overcharging and deep discharge.
- Photo-Voltaic (PV) generation includes PV panels and controllers. PV panels transform sunlight into electricity, generated in direct current (DC). Solar controllers protect batteries from overcharging and deep discharge.
- The generated energy is stored in batteries, which must have enough capacity to meet the demand of the consumers during some days without generation.
- DC power leaving batteries is transformed by the inverters into AC, which is more suitable for most electrical appliances.
- Electricity is distributed to consumption points by wires. Distribution can be through individual systems (a generation point that produces energy just for its own consumption) or through microgrids (a generation point supplies more than one consumption point). Microgrids have a radial scheme [28] (form of a tree as in Fig. 5).
- Every consumption point has its own energy and power demands, i.e. daily electrical energy requirements and total power of installed equipments. Consumption points fed by microgrids must have meters to control the energy consumption and, in some cases, limit the maximum consumption.
- Energy losses in batteries and inverters are included as a factor that increases the demand for each consumption point. Energy losses in the wires are also considered at the consumption points fed with microgrids.

4.2. Optimization model

Linear programming is a powerful tool that allows quickly modelling complex real problems in a mathematical way. This technique consists of optimizing (maximizing or minimizing) a linear function subject to a set of constraints expressed through linear inequalities. A linear programming model is described by the following elements: the parameters are the data required to solve the problem; the variables are the aspects of the solution that are required for its definition; the objective function is what we want to optimize; and the constraints are the limitations of the problem. Mixed integer linear programming (MILP) is a particular type of linear programming, which permits the utilization of float, integer and binary variables, thus complicating the solving process that is carried out by specific software. MILP has been used for modelling and solving many problems since the 50's and the last advances in computation have extended its use as an exact solution process (obtaining the optimal solution) which is now a dynamic research area [29]. Therefore MILP has gained acceptance as a tool for providing optimal or near-optimal solutions to real-life strategic and operational planning problems [30, 31, 32, 33]. Specifically its adequacy for solving problems as the design of electrification systems using renewable energies has been demonstrated [34].

In this context, a MILP model was recently developed and successfully utilized in the definition of two real projects in the Andean mountains of Peru [5, 10]. In this study, it will be applied for the design of Santo Antão and Santiago projects (Section 5). The model allows designing stand-alone electrification systems for rural communities with wind-PV energies, considering microgrid definition and micro-scale resource variations. It aims to minimize the cost of the initial investment, a critical limitation in this type of projects [3], taking into account system configuration and technical criteria of the equipment that may be used (for more details see [10]). Next, the parameters, variables, objective function and constraints of the model are described.

- Parameters:
    - *Demand:* Energy and power requirements of each demand point (houses, schools, health centers, etc.) and days of autonomy.
    - *Generation and accumulation:* Wind turbines (types, cost, nominal power, energy generated and maximum number at one generation point), PV panels (types, cost, nominal power, energy generated and maximum number at one generation point) and batteries (types, cost, capacity and discharge factor).
    - *Definition of the network:* Distance between points, wires (types, cost per meter including microgrid infrastructure, resistance and maximum intensity), nominal voltage and maximum voltage drop.
    - *Equipment:* Controllers and inverters (types, cost and maximum power) and meters (cost).
- Variables:
    - *Equipment (generation, accumulation, distribution):* Integer variables indicating the number of each type of equipment to be installed at each point.

  - *Definition of the network:* Binary variables indicating if two points are joined with a type of wire, and real variables for power and energy flow between two points.
- Objective function: To minimize the cost of the investment considering wind turbines, wind controllers, PV panels, solar controllers, batteries, inverters, meters, and wires.
- Constraints:
  - *Generation and accumulation:* At each point, an energy and power balance is realized. Batteries must be installed in generation points and its capacity must cover the days of autonomy considering the demand and the discharge factor.
  - *Definition of the network:* Relationship between energy and power flows and the existence of a wire is established. The installed wire must satisfy maximum voltage drop and maximum intensity. Microgrid structure is radial.
  - *Equipment:* Installed wind and solar controllers must be adequately powered for wind turbines and PV panels, respectively. Due to technical constraints, an adequate wind controller is considered to be included in each wind turbine. Inverters must satisfy power demand. Controllers and inverters must be installed in generation-accumulation points.

4.3. Input Data

In order to carry out a consistent economical comparison with the diesel system (Section 6), most of the data are taken from the previous study in Figueiras and Ribeira Alta communities [2]. The same input data are also used for Santiago project design analysis. Next, we present the main characteristics of the equipment considered:

- Wind turbines (3 types): nominal power: 600, 3500 and 7500 W; cost: \$4856, \$11794, \$25000.
- Solar panels (3 types): nominal power: 210, 2100 and 4200 W; cost: \$1488, \$14881 and \$29762.
- Batteries (2 types): capacity: 840 and 1600 Wh/day; cost: \$380.3 and \$578.7; efficiency: 85%; autonomy: 1 day; minimum discharge rate: 0.5.
- Inverters (3 types): maximum power: 300, 4000 and 5000 W; cost: \$377, \$3175 and \$4762; efficiency: 85%.
- Grid wire: cost: \$5/m.
- Electricity meter: cost: \$50 each.

The considered wind turbines are commercial ones, whose price includes a 20 m tower and electronic controllers. The costs of the 600 W and 3500 W nominal power wind turbines were supplied by turbine manufacturers while the 7500 W wind turbine is the same considered by [2]. Solar panels, batteries and inverters types and costs are the same considered in [2]. The storage systems are designed for 1 day of autonomy, covering possible days of low generation. A standard grid wire cost is assumed for low voltage line [10].

As explained in Section 2.2, users of Santo Antão and Santiago projects have similar characteristics and electricity requirements, therefore the same energy and power demands are considered for both studies. According to [2], an energy demand of 700 Wh/day (taking into account eventual increases in the next years) and a power demand of 200W are considered for each house. Schools and health centers demands are assumed to be the double of the houses demand. Total net energy demands are 126.7 kWh/day and 30.8 kWh/day respectively in Santo Antão and Santiago projects. Additionally, the wind resource maps considered in each project are those shown in Figures 3 and 4 (Section 3) and a solar resource of 4.8 kWh/(m^2·day) is assumed (Section 2).

5. Electrification system design proposal

In this Section the design proposals of the Santo Antão (Figueiras and Ribeira Alta) and Santiago (Achada Leite) electrification projects are described. The optimization model previously described is applied in order to properly support the design. Three design configurations are developed and compared in the 2 studied projects. These configurations are calculated with the MILP model: in one of them the model is used (*C2*) directly whereas for the other two (*C1* and *C3*) little adaptations were needed. Next, we present the 3 design configurations, we justify their analyses and we explain how they were obtained.

1) *Individual generation (C1)*: Individual systems are installed in each demand point (every demand point is generating just for its consumption and no microgrids are installed). As stated in the introduction of this paper, this is the common choice when electrifying isolated communities through autonomous systems using renewable energies [6, 7].
2) *Individual generation and microgrids with generation in demand points (C2)*: In order to overcome individual systems' limitations [10], microgrids and individual generation points are allowed, so the solution obtained may be a combination of some microgrids and some individual generators. In this case generators are permitted to be installed only close to the demand points' locations.
3) *Individual generation and microgrids with generation in best resource area (C3)*: Microgrids and individual generation points are allowed, and the area of best wind resource (indicated by an "X" in Fig. 3 and 4) is considered as possible location for generation equipment. This solution is analyzed to evaluate the possible advantage of taking profit of the best resource areas with generators far from the demand points.

5.1 Santo Antão project

As stated before, Figueiras and Ribeira Alta communities are currently electrified by 2 grids (one for each community) with diesel generators and therefore no cable cost is considered for the connection between users where the cable is already present. Moreover, as explained in sub-Section 3.1, the installation of wind turbines near to demand points is not considered due to the high slope steepness and so only solar generation is considered for them (C1 and C2). On the other hand, both wind and solar generations are considered in the best resource area for C3. Next we present the solutions obtained, whose initial investments and design configurations are shown in Table 1 and in Fig. 6, respectively.

- *Configuration C1*. Solar panels are installed at each demand point in order to cover their demand.
- *Configuration C2*. Two solar microgrids are implemented (left part of Fig. 6). Solar panels with a total power of 30.2 kW and 12.4 kW are installed in the centers of each microgrid in order to reduce voltage drops. This configuration reduces initial investments of around 38.8% in comparison with C1 (Table 1). The existing low voltage lines are shown by the thin lines in Fig. 6.
- *Configuration C3*. This design configuration consists of a single microgrid connecting both communities with generation in the high resource area highlighted in Fig. 3. The selected generation point (indicated by a triangle in the right part of Fig. 6) is located at around 200 m a.s.l.. Four wind turbines of 7.5 kW and one turbine of 3.5 kW nominal powers are installed in the generation point, in order to cover users' energy demands. The low voltage lines to be constructed are shown by the thick dark lines in Fig. 6. The resulting configuration reduces the initial investment of 61.3% and 36.8% in comparison with C1 and C2 respectively (Table 1).

Table 1. Costs ($) comparison of the different design configurations

Configuration	**Santo Antão project**	**Santiago project**
C1	769297	187868
C2	470564	126373
C3	297594	90380

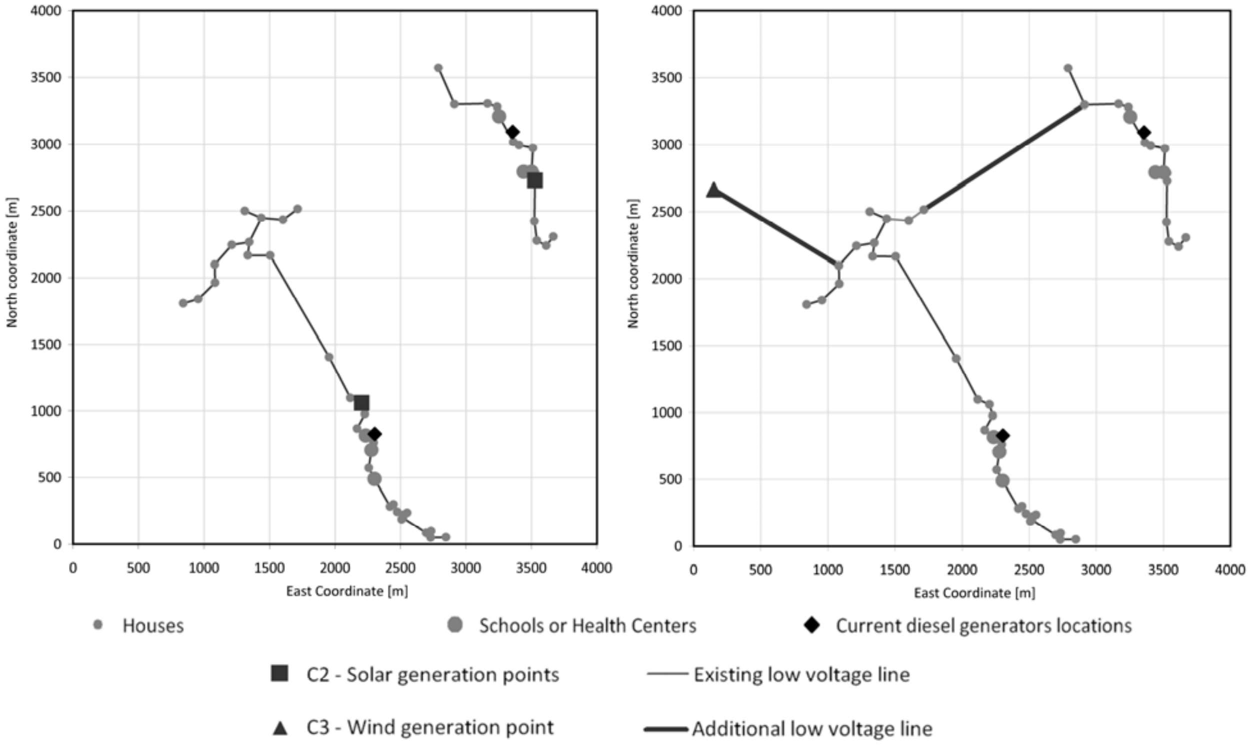

Fig.6. Configurations C2 (left) and C3 (right) for the electrification of Santo Antão project

5.2 Santiago project

Next we present the solutions obtained in Santiago project, whose initial investments and design configurations are shown in Table 1 and in Fig. 7, respectively.

- *Configuration C1*. Due to low wind resource at community points, the best design is obtained by installing solar panels in all demand points.
- *Configuration C2*. A single microgrid with solar generation in a point located in the center of the community, in order to reduce voltage drops, is obtained (left part of Fig. 7); a total power of 10.7 kW is required to cover the all users' demands. This configuration reduces initial investments of around 32.7% in comparison with C1 (Table 1).
- *Configuration C3*. This design configuration consists of a single microgrid but with generation about 600 m north from the houses. The generation point (indicated by a triangle in the right part of Fig. 7) is located on the top of a small hill at around 100 m a.s.l. One wind turbine of 3.5 kW and another of 7.5 kW nominal powers are installed in order to cover users' energy and power demands with the minimum initial investment. The resulting configuration permits the exploitation of a good wind resource and reduces the initial investment of 51.9% and 28.5% in comparison with C1 and C2 respectively (Table 1).

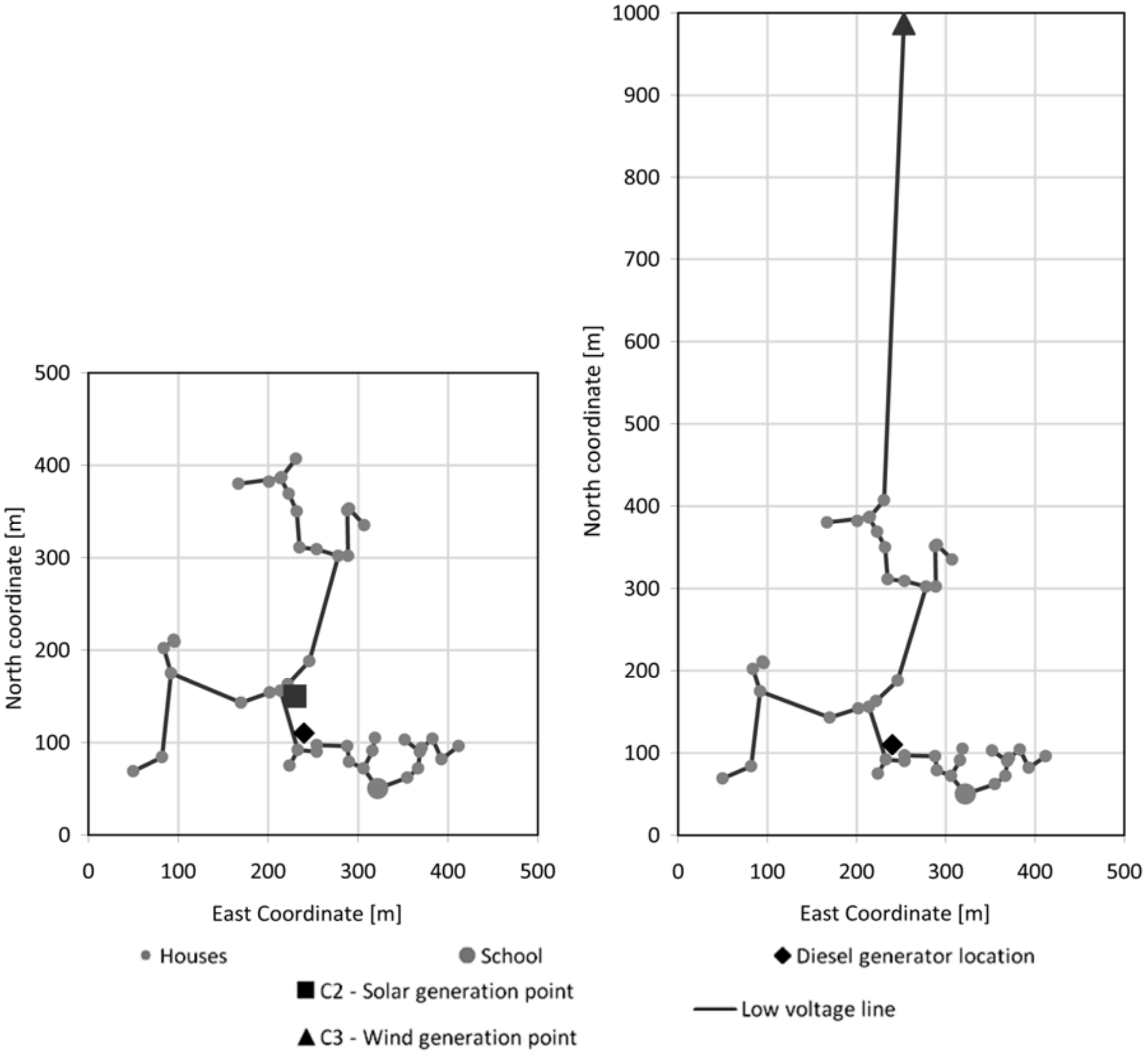

Fig.7. Configurations C2 (left) and C3 (right) for the electrification of Santiago project

6. Economic and environmental assessment

An economic and environmental analysis of the proposed system is hereby carried out. The following two design configurations are compared:

- “Proposed configuration”: refers to the design proposed in this study. In both studied projects the most suitable solution is one microgrid and generation in best resource area (C3, see Section 5).
- “Diesel configuration”: consists of a diesel generator and a centralized microgrid connecting the whole community. This is the conventional strategy in Cape Verde and the current electrification system in Figueiras and Ribeira Alta (one microgrid in each community).

As stated in Section 2.1, a 2010 GEF study [2] proposed the replacement of current diesel systems in Figueiras and Ribeira Alta (Santo Antão project) with 2 hybrid wind-solar-diesel systems. Even if the design of the hybrid systems in [2] is not complete (e.g. wind turbines locations is not analyzed), a detailed analysis of initial investment and annual costs of both systems was developed in that study. Therefore, in order to carry out a consistent economical comparison, most costs utilized here were directly taken from there (such as the equipment costs described in Section 4.3) or, when this was not possible, they were extrapolated in strictly accordance with [2]. Table 2 details how the different costs considered for the "Proposed configuration" and the "Diesel configuration" were assessed.

Table 2. Costs considered in the economical comparison

		Santo Antão project		Santiago project	
		Proposed configuration	Existing diesel configuration	Proposed configuration	Diesel configuration
Initial investment	Equipment	It was taken directly from [2], a part from cables, 600 W and 3.5 kW wind turbines	No cost (Already existing)	It was taken directly from [2], a part from cables, 600 W and 3.5 kW wind turbines	It was taken directly from [2], a part from cables
	Transportation, Installation and Technical Assistance (T & I & TA)	It was estimated according to hybrid system costs in [2]	No cost (Already existing)	Proportional to proposed configuration cost in Santo Antão project	Half of proposed configuration cost
Annual costs	Equipment replacement	It was taken directly from [2]. All wind turbines have the same cost	It was taken directly from diesel system costs in [2].	It was taken directly from [2]. All wind turbines have the same cost	It was extrapolated from diesel system costs in Santo Antão project
	Operation & Maintenance (O & M)	It was estimated according to hybrid system costs in [2]	It was taken directly from diesel system costs in [2].	Proportional to proposed configuration cost in Santo Antão project	Proportional to diesel system costs in Santo Antão project
	Fuel	No cost (no fuel required)	It was taken directly from diesel system costs in [2].	No cost (no fuel required)	Proportional to diesel system costs in Figueiras and Ribeira Alta

Regarding the "Proposed configuration" the following costs are considered:

- Initial investment: include equipment costs and the transportation, installation and technical assistance (T & I & TA) costs. The equipment costs are those reported in Table 1 for configuration C3, while the T & I & TA costs are estimated according to hybrid wind-solar-diesel configuration costs [2]. As in Santo Antão project there is a single generation point, these costs are lower that the sum of the two separate systems (60% of the T & I & TA costs of 2 separate systems). In Santiago project, T & I & TA costs are calculated proportionally to the lower quantity of equipments to be installed.

- Annual costs: include equipment replacement, operations and maintenance costs. The equipment replacement costs of inverters, batteries, solar panels and wind turbines considered in the proposed configuration are taken from [2]. In Santo Antão project the operations and maintenance (O & M) costs are estimated according to [2], taking into account that in the proposed configuration there is a single generation point for both communities (60% of the O & M costs of 2 separate systems). In Santiago project, the O & M costs are calculated proportionally to the lower quantity of equipments to be installed.

Regarding the “Diesel configuration” the following hypotheses are considered:

- Initial investment: In Santo Antão project no initial costs are considered as diesel generators are already installed; this is a conservative assumption as it is highly probable that those generators should be replaced soon due to their age (they were installed more than 10 years ago). In Santiago project a diesel generator of 20 kW nominal power is assumed to be installed in order to cover total power and energy demand (around a quarter of Santo Antão project demand). A single microgrid with generation in the center of the community is assumed (indicated by a black diamond in Fig. 7) minimizing grid length and voltage drops. Neither batteries nor inverters are installed in this case (again a conservative assumption as batteries could be needed if a continuous supply is preferred). Transportation, installation and technical assistance costs of the diesel generation are considered to be half of proposed configuration T & I & TA costs.
- Annual costs: In Santo Antão project, the annual costs of the currently installed diesel generators (40 kW nominal power each) are assessed in detail in [2]. The annual costs include also the fuel cost that is based on 2010 diesel price of 1.33 $/l [2]. As it is highly probable that this price will increase in next years, an analysis considering an annual increase of 5% on current fuel cost is additionally carried out. The fuel transportation cost is included in the diesel generator O & M costs that are generally higher than those of the wind and solar systems. In Santiago project, annual costs of the diesel system are calculated proportionally to Santo Antão project, considering the lower annual energy production.

The obtained initial investment and annual costs of the analyzed configurations are presented in Table 3 considering current exchange rate of 1 US$ (United States Dollar) = 84 CVE (Cape Verde Escudos). The proposed configurations require high initial investments, however the diesel configurations have a much higher annual costs (due basically to fuel cost).

Table 3. Investment and annual costs ($) of proposed configuration and the diesel configuration

		Santo Antão project		Santiago project	
		Proposed configuration	Diesel configuration	Proposed configuration	Diesel configuration
Initial investment	Equipment	297594	0	90380	18274
	T & I & TA	106429	0	31929	15964
	Total	**404023**	**0**	**122388**	**34238**
Annual Costs	Equipment replacement	6192	24429	1700	5938
	O & M	5000		1500	
	Fuel	0	21767	0	5291
	Total	**11192**	**46195**	**3200**	**11230**

Fig. 8 shows the cumulative costs' evolutions of the analyzed configurations in Santo Antão and Santiago projects. The black lines represent the proposed configuration while the grey lines refer to the diesel configuration (the continuous line considering a constant fuel cost while the dotted lines considering an annual increase of 5% in fuel cost). The payback times of the proposed configuration are 11.5 years and 11 years respectively in Santo Antão and Santiago projects. These payback times decreases to 9.7 and 9 years as diesel fuel price increases of 5% annually. Therefore, both proposed electrification projects' configurations result economically beneficial as the expected lifespan of the project is much longer than 12 years. It should be noted that, if the proposed configuration in Santo Antão project had been considered since the beginning of the project design (therefore including the actual initial investments of the diesel systems) its reliability would have been further increased. In this case, the payback time of the proposed configuration in comparison with the diesel configuration would have been around 7.5 years.

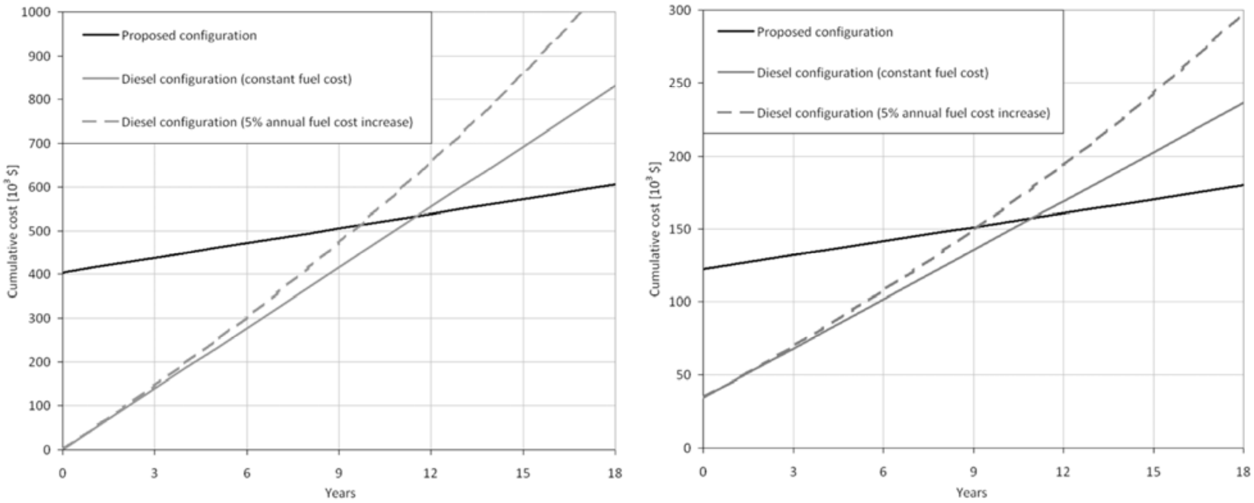

Fig.8. Cumulative costs' evolution of the proposed and diesel configurations in Santo Antão (left) and Santiago (right) projects

As stated in Section 2.1, the GEF study [2] could not be considered a complete design analysis due to some limitations, such as the roughly estimation of wind energy production from a remote meteorological station (resulting in a much higher wind resource in comparison with Cape Verde wind atlas [18]) and the lack of turbines micro-siting analysis. Even thus, a costs comparison between the hybrid wind-solar-diesel system defined in [2] (grey line) and the proposed configuration (black line) is shown in Fig. 9. The proposed configuration, completely relying on renewable energies, is economically beneficial even in comparison with that system: it has a similar (slightly higher) initial investment cost but a lower annual cost resulting in a 2 years payback time.

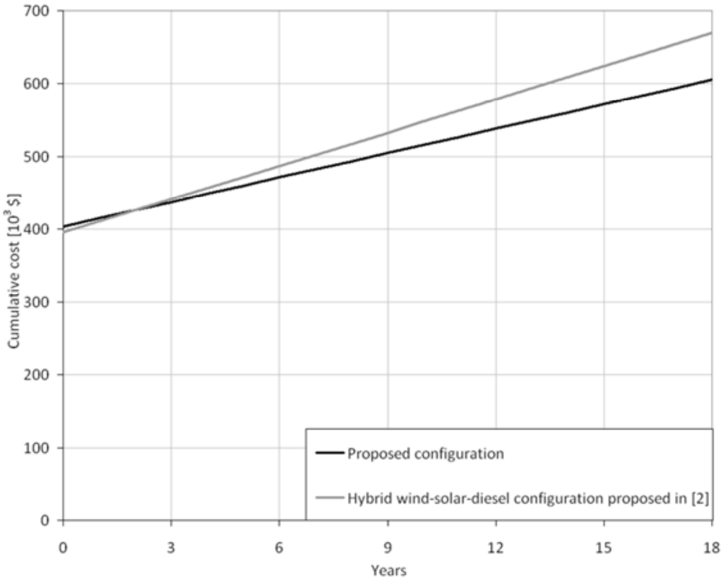

Fig.9. Cumulative costs' evolution of the proposed configuration and the system proposed in [2] in Santo Antão project

Regarding environmental aspects, hardly assessable in detail, it is known that wind and solar technologies have a low impact; anyhow, it should be considered that most critical components are batteries that contain substances harmful to the environment and must be correctly recycled. On the other hand, the utilization of a diesel generator leads to the emission of different contaminant gases, such as SOx, NOx and CO_2 [35]. Considering only carbon dioxide emission, assuming an emission rate of 0.65 kg CO_2 / net-kWh [35], the emissions of the diesel generators are around 33.4 tCO_2 and 8.1 tCO_2 per annum respectively in Santo Antão and Santiago projects, which can be saved by the proposed configurations based on renewable energy.

7. Conclusions

In this study, the designs of off-grid electrification projects based on hybrid wind-PV energies in 3 rural communities in Cape Verde are analyzed. The studied sites are Figueiras and Ribeira Alta in the island of Santo Antão (Santo Antão project), and Achada Leite in the island of Santiago (Santiago project).

Firstly the wind resource assessment is realized analyzing wind resource variation at a micro-scale. While solar resource is considered uniform, the detailed wind resource assessment shows high wind variability in all the communities, with low resource within them, but greater resource in areas some hundreds meters far. Secondly, a mathematical MILP model for the optimization of the systems design evaluating combination of microgrids and individual generators is outlined and applied.

For both projects, three different configurations are studied: 1) all the points with individual generation; 2) microgrids and individual points are allowed with generation only in demand points; and 3) microgrids and individual points are allowed with generation in areas with best resource (far from demand points). Results show that when generating only in demand points and allowing microgrids, two microgrids are formed in Santo Antão Island (one for Figueiras and one for Ribeira Alta) and one microgrid is formed in Santiago Island (for Achada Leite). These configurations allow saving more than 30% of the initial investment comparing with individual generation configurations. Besides, when generating in windy but remote points, initial investment can be additionally reduced using more powerful equipment achieving a higher energy produced / cost ratio: further cost decreases of around 30% were obtained in comparison with the configurations that consider only generation in demand points. These finally proposed configurations enable a cost reduction of more than 50% in comparison with the one that considers all individual generation points.

Besides the lack of continuous fuel supply and important reduction in greenhouse gases emissions, the renewable energy system proposed in this study resulted to be economically beneficial in comparison with a grid based on a diesel generator with a maximum payback time lower than 12 years even in most conservative analysis.

Acknowledgment

This paper was supported by the Spanish Ministry of Education (FPU grant AP2009-0738), the MICINN project ENE2010-15509 and by the Centre for Development Cooperation of the Universitat Politècnica de Catalunya. M.R. is very grateful for all the assistance and support provided by people of the ECREEE office in Praia, to Daniel Graça for the information on diesel generator grids in Cape Verde, to Gustavo Herrera for the treatment of topographic maps and to Joaquin Mataix for the consultancy about wind turbines characteristics and costs. The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the paper.

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Heuristic indicators for the design of community off-grid electrification systems based on multiple renewable energies

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Article published as [Ranaboldo M, Ferrer-Martí L, García-Villoria A, Pastor Moreno R. Heuristic indicators for the design of community off-grid electrification systems based on multiple renewable energies. Energy. 2013 2/1;50(0):501-12] © [copyright Elsevier]

Abstract

Off-grid rural electrification project configurations which consider hybrid generation systems based on multiple renewable sources and the implementation of micro-grids are the most promising design solutions. The efficient design of those systems is a complex task that is facing several technical issues such as limited time and resources available for the purpose, especially in developing countries. This study proposes indicators for supporting and improving the design of community off-grid electrification projects considering hybrid generation and micro-grids. A Grid Generation Score (*GGS*) is defined in order to identify most promising locations for being the generation point of a micro-grid. The No-Generation Score (*NGS*) and the Independent Generation Score (*IGS*) evaluate respectively if a point should be reliably connected to a micro-grid or should better be an independent generation point. All indicators could be easily and quickly calculated at a very first stage of the plan of a community project requiring as input data only demand and resource distributions in the studied area. It is shown that the utilization of proposed indictors can enhance the design of stand-alone community electrification projects based on renewable energies.

1. Introduction

Off-grid electrification systems based on the use of renewable energies are a reliable solution to supply energy to isolated communities: these systems produce electricity in a clean and environmentally respectful way and their cost is often lower than national grid extension [1]. Furthermore, using locally available resources, these systems are not dependent from external resources, therefore increasing projects long-term sustainability

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[2, 3]. In this sense, photovoltaic systems have been widely used in the last decades in order to cover basic household's needs and wind systems are receiving increasing attention [4]. The design of a community off-grid electrification project based on renewable energies should result from a balance between the available energy resources and the energy/power requirements of the users (i.e. demand points such as houses or public buildings). Most isolated rural communities of developing countries are characterized by dispersed house distribution in areas of few squared kilometres and variable energy resources. In particular, wind resource is the most scattered and important resource variations have been encountered within the same community in mountainous context [5]. Furthermore, the energy demand is generally limited, i.e. lower than 1 kWh/day per user, and may not be uniform as public buildings, such as schools or health centres, have higher energy requirements in comparison with family houses.

In this context, hybrid systems that combine different resources and micro-grids, where the energy is produced in a certain point and distributed through an electric grid to other consumption points, proved to be most reliable design configurations [6, 7]: they can lead to an increase in efficiency and supply quality and a decrease in installation costs. Firstly, a system using a combination of different renewable sources has the advantage of balance and stability that offers the strengths of each type of sources that complement one another [6]. In particular, hybrid solar/wind systems are one of the most promising generation options [8]. Secondly, micro-grids installation could lead to an important decrease in the final cost of energy in comparison with independent generators, i.e. a demand point that generates energy just for its own consumption, and enhance the flexibility of the system [7, 9]. In fact, areas of high resource could be exploited by micro-grids' utilization taking advantage of the economy of scale: more powerful generators are installed in sites with better resource. In scattered communities with isolated users the combination of independent generators and micro-grids is generally the cheaper design solution [10].

When considering hybrid systems and the combination of independent generation points and micro-grids the complexity of the design is relevant and is facing several technical issues. The selection of grid generation points and the definition of which points should be connected to a certain micro-grid and which not are complex tasks, especially when resource (e.g. the wind) is highly disperse [10]. A typical community configuration in mountainous context has houses located in the valley while best wind resource is at the hill/mountain-top: the selection of the adequate system configuration (which types of generators consider, where to install them and which points connect) should result from a balance between resource potential differences, the houses distribution and the distance from the high resource area. Furthermore, when multiple renewable energies are considered (hybrid systems), the identification of the most adequate combination of generation technologies is not straightforward. In this context, optimization models should be used and are currently utilized in order to properly design the electrification system for independent generation [11, 12, 13]. However, optimization models generally require considerable computational time and resources that are hardly available in rural electrification projects. In practice, many times a fast solution is expected and the design of those systems basically relies on the experience and expertise of the promoter. Furthermore, there is lack of support tools for the design of community projects considering a combination of independent generators and micro-grids [14].

Heuristic methods (or simply “heuristics”) are a technique commonly used in combinatorial optimization [15] in order to accelerate the solving procedure or to make viable the solution to some optimization problems that cannot currently be optimally solved even by super-computers. Heuristics will generally not guarantee the optimal solution but when well designed the obtained solutions can be expected to be fairly close to the optimum value [16]. This study proposes heuristic indicators that characterise and classify the points of a community to assist the design of a project. These indicators evaluate the a-priori suitability of a point of being: first, a point that is fed by a microgrid and just consuming energy or a point with energy generation; and second, among the generation points, which one provides energy only for them or which ones fed also other points with microgrids. In order to present a practical utility, all the indicators could be easily and quickly calculated at a very first stage of the design of a community project requiring solely the knowledge of houses positions and energy requirements and data about the resource (wind and solar) in the area. In Section 2 the components of a hybrid electrification system are described and current models for the design of those systems are briefly resumed. The calculations of the proposed indicators are described in Section 3 and the performance of such indicators is finally analyzed in 2 mountainous communities in Peru: El Alumbre and Alto Peru (Section 4).

Proposed indicators could be applied in several ways in order to support and improve the design of community off-grid electrification projects based on renewable energies. First, the indicators could be used in order to select most promising generation points in currently available models where the pool of grid generation points is limited [10, 17]. Another relevant application of such indicators is their inclusion in heuristics algorithms that aim to optimize the design of off-grid electrification projects. Many heuristics (e.g. greedy) currently used to solve location optimization problems, such as the design of community electrification projects, divide the solving process into various steps; in each step an element is selected from a ordered list of possible candidates (i. e. candidate list) and included in the solution. In this context, the definition of a parameter that could be calculated a-priori in order to rank the elements of the candidate list is a promising approach for heuristically solving location problems (e.g. [18, 19]): the indicators proposed in this study aim to provide such a tool for heuristics design. In this sense, although developing a design procedure is not the objective of this paper, a simple greedy-heuristic based on the indicators for off-grid electrification design is presented and tested (sub-Section 4.3). Thus, we can verify that, even if the heuristic used as the design procedure is very simple, the indicators are useful to generate solutions close to the optimal ones. As a final application, such indicators could be used as an efficient design support tool by those organizations that does not have access to any optimization model and whose decisions rely currently just on promoter experience.

2. Off-grid electrification systems and current models for its design

The scheme of the elements involved in a wind - photovoltaic autonomous electrification system is as follows (Fig. 1):

1) Generators: produce energy in alternating (wind turbines) or direct (solar panels) current
2) Controllers: convert current and control the charge/discharge of the batteries.
3) Batteries: store the energy produced by the generators, receive and supply electricity at direct current (DC).
4) Inverters: convert direct to alternating current (AC) at the nominal voltage.
5) Electric cables: configure the micro-grid that distributes the energy.
6) Electric meters: measure the energy consumed at the consumption points.
7) Consumption points: consume the energy.

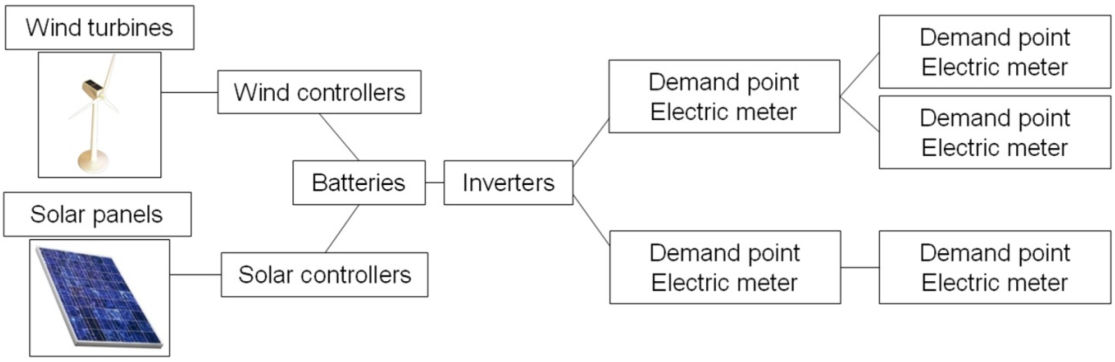

Figure 1 – Scheme of the elements involved in a hybrid wind-photovoltaic electrification system [14]

If there is only one user (i.e. demand point) connected to the generators/controllers/batteries/inverters group (a generation point) than we called it an “independent generation point”, while if there are multiple users connected by electric cables they form a “micro-grid”. As much higher costs and a more complex electrical design are required when considering a micro-grid with multiple generation points (annular configuration), micro-grids with a single generation point (radial configuration as in Figure 1) are generally preferred in rural electrification projects [17, 20]. The radial micro-grid configuration is then considered in this study.

At present, many studies deal with the design of stand-alone electrification systems in rural villages [2, 12, 21, 22, 23]. However, the research is mainly focused on the study of the best combination of energy sources of an independent generation system without considering micro-grids design and wind resource variability among different point of an area. In this sense, HOMER by NREL is the most widely used decision support tool, which simulates and compares costs throughout the lifespan of a project for various electrification scenarios [24].

In the last years, Ferrer-Martí et al. [10] developed a mathematical model that optimizes the design and localization of micro-grids and wind turbines defining all electric equipments to be installed, taking into account voltage drops along the cables and wind resource variability. The model has been implemented successfully in the design of rural electrification projects in Peru, showing how wind micro-grids could highly reduce installation costs in mountainous environment. Recently a new model has been developed considering hybrid wind-solar generation [14]. Due to its high computational requirements when the size of the studied community grows, the application of the optimal mathematical model may be difficult depending on the available time, the size of the community and the specific design requirements.

When a fast solution is desired, heuristics approaches should be tried to solve the problem. To our knowledge, VIPOR model developed by Lambert and Hittle [17] is the unique heuristic algorithm encountered in literature that faces the presented problem. This model designs off-grid electrification projects considering radial micro-grids, hybrid generation systems and wind resource changes in an area. Main drawbacks of VIPOR model are the limited pool size (10 as maximum) of possible grid generation points, the no-consideration of some electrical constrains, such as the voltage drop, and the assumption of a uniform resource in the area for independent generation. Approaches similar to the one of VIPOR [17] have been utilized at a more regional level in order to decide which villages should be connected with national grid and which not, as a function of the population density [25].

3. Proposed indicators

This study proposes some indicators for supporting and assisting the design of off-grid rural community electrification projects. Figure 2 shows a typical design solution of an off-grid electrification project that considers both independent generation points and micro-grids for a community. In such design configuration, three different types of points are present:

- Grid Generation Points, where the energy is produced and distributed to others demand points through a distribution network (radial micro-grid);
- No-Generation Points: points connected to a micro-grid and just consuming energy;
- Independent Generation Points: points producing energy just for their own consumption and not connected to any micro-grid.

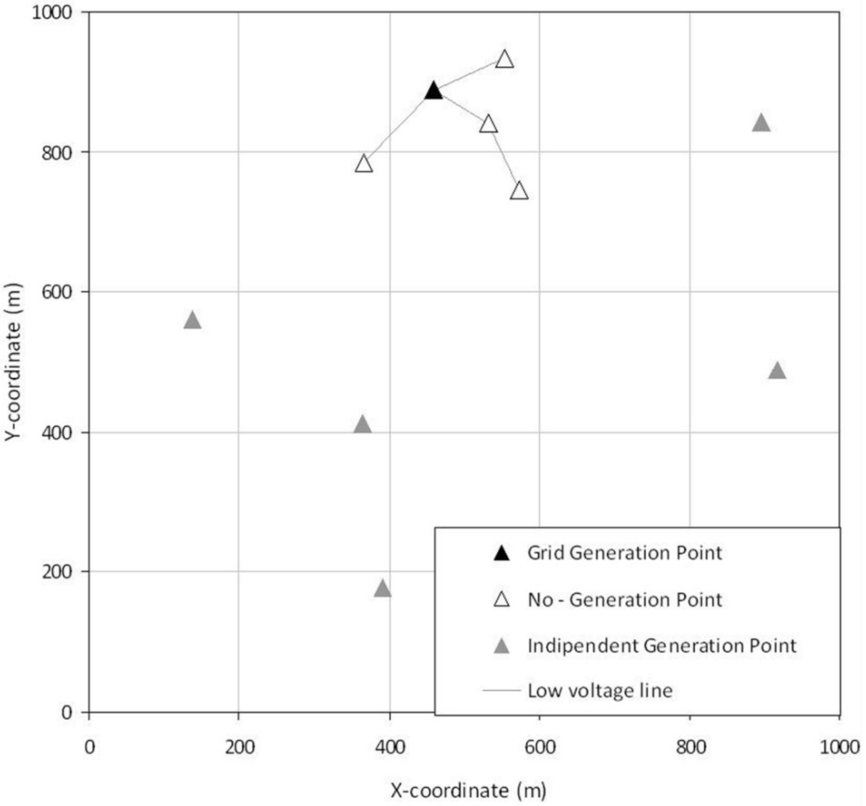

Figure 2 – Typical design of an off-grid electrification project with radial micro-grids and independent generation points

A priori, the identification of the characteristics of a point for being a Grid Generation Point, a No-Generation Point or an Independent Generation Point depends basically on the distribution of the energy resources (e.g. wind and solar) and the community configuration (demand distribution). In this sense, the following features are the most representative in order to characterize a single point: outstanding resource potential in comparison with the surrounding points and the energy demand concentration around the point. In the following the term "potential" is used as a synonym of resource and refers to the renewable energy potential in a specific site, not to be confused with the "electric potential".

Generally, a Grid Generation Point is located close to other demand points, so that it results reliable to connect them by a micro-grid. Furthermore, it should have a high potential in comparison with the surrounding points, so that the generators of the micro-grid could be efficiently installed there. Therefore a Grid Generation Point should have an outstanding potential and a high energy demand concentration around it. A No-Generation Point should also have a high demand concentration around it in order to be profitably connected to a micro-grid, while it should have a lower potential in comparison with the surrounding points. On the other side, an Independent Generation Point should be isolated (low demand concentration around it) and its potential should be basically similar to the one of the surrounding points. Table 1 resumes those characteristics and proposes the two following indicators that evaluate the two features previously defined:

1) A Resource Indicator (*RI*) that evaluates how much the resource (potential) of a point outstands among the potential of the surrounding points. It does not correspond to the absolute potential of the point; instead it represents the relative potential of the point in comparison with the others. In Table 1, a “Positive” *RI* means that the point has a high potential, a “Null” *RI* means a similar potential and a “Negative” *RI* a low potential in comparison with the surrounding points.
2) A Demand Indicator (*DI*) that evaluates the demand concentration around the reference point considering the number of demand points weighted for their distance from the analyzed point. Its value is always positive and could be high or low.

Table 1 – Basic features of Grid Generation Points (GGP), No-Generation Points (NGP) and Independent Generation Points (IGP)

Indicator	*GGP*	*NGP*	*IGP*
Resource Indicator	High (Positive)	Low (Negative)	Null
Demand Indicator	High	High	Low

The heuristic indicators that evaluate the a-priori suitability of a point of being a grid generation point, a no-generation point or an independent generation point, are defined, respectively, the Grid Generation Score (*GGS*), the No-Generation Score (*NGS*) and the Independent Generation Score (*IGS*). Those values could be calculated as a combination of *RI* and *DI*.

It should be noted that a Grid Generation Point could be ideally every point in a certain area (a demand or a no-demand point), even if, as encountered in literature, generation points are generally restricted to be located close to the users [20]. The definition of the *GGS* calculation is so that it is evaluated for all the points and it could help in selecting most promising (demand and no-demand) points for being Grid Generation Points.

In this Section, a Hybrid Potential Indicator is firstly defined in order to consider different renewable energy resources (subsection 3.1); then the calculation of the Resource and Demand Indicators (subsection 3.2) and of the *GGS, NGS* and *IGS* (subsection 3.3) are proposed.

3.1 Hybrid Potential Indicator

When designing off-grid electrification projects based on hybrid renewable energy systems, it is fundamental to define a resource indicator that considers the different renewable resources that could be potentially exploited in an area.

The levelized cost of electricity (*LCE*) is the most often used criterion when comparing electricity generation technologies or considering grid parity for emerging technologies such as solar, wind and hydro [26]. The *LCE* is basically the ratio between the total cost of a project and the energy output expected through its lifetime. Following a similar approach, a potential indicator function *P()* for off-grid generation could be calculated as by equation (3.1).

$$P(ED) = \frac{ED}{CG(ED)} \tag{3.1}$$

ED is the energy demand to be supplied and function *CG(ED)* is the minimum generation cost, considering the best hybrid generators combination, in order to cope with that energy demand *ED*. For the function *CG()* calculation, all different combinations of hybrid generation (e.g. wind turbines and solar panels) are considered and the one with minimum cost is selected.

Due to the economy of scale of most renewable energy technologies, the function *P()* is not constant and generally tends to increases with an increase in *ED*. As the energy demand to be covered from a reference point is not know a priori (how many demand points will be connected with a micro-grid to a certain generation point), the function *P()* for a certain *ED* could not be directly utilized as the resource indicator. Variation of the function *P()* value as a function of *ED* is analyzed for a demand point of a real community in which wind and solar energies are utilized (Figure 3). The considered point is located in the centre of El Alumbre community (more details about that community are reported in subsection 4.1). The energy demand varies from the one of the own point (380 Wh/day) to the one of connecting the whole community (15190 Wh/day). Three different solar panels and four small wind turbines are considered as possible generation options [14]. Figure 3 shows how function *P()* tends to increase when considering a higher *ED* till reaching the ratio between the generated energy and the generator cost of the most powerful technology option (with function *P()* ≈ 1.6). It should be also noted that this trend is not constant and various fluctuations are encountered reflecting the different generation options (hybrid combinations of solar and wind generators) obtained at each value of *ED*.

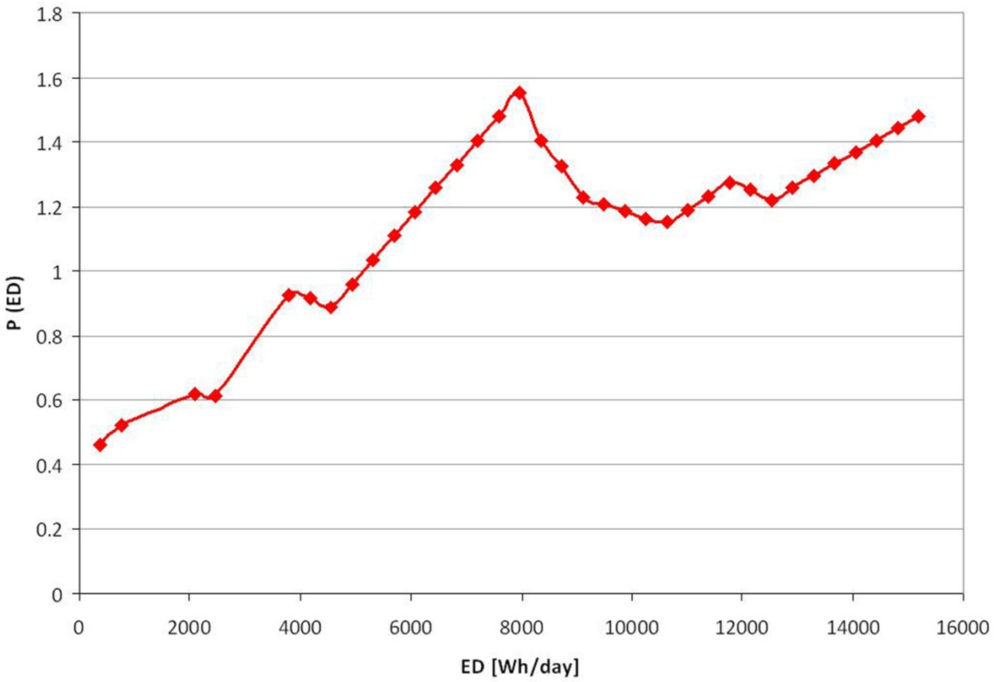

Figure 3 – P value as a function of the Energy demand ED to be covered.

Considering this issue, it is proposed to utilize a resource indicator that corresponds to the average value of the function *P()* for different *ED*. The different energy demands considered represent the different numbers of demand points that could be connected to the point where the generation system is installed. Therefore, the Hybrid Potential Indicator (*HPI*) of the point *i* is calculated as in equation (3.2):

$$HPI_i = \frac{\sum_{k=1}^{n_i} P\left(\sum_{j \in PP_i(k)} ED_j \right)}{n_i} \tag{3.2}$$

ED_j is the energy demand of point j, $PP_i(k)$ is the set of k points closest to i, n_i is the total number of points in a given radius L_{max} around i. L_{max} represents the maximum distance between a demand point and the generation point of a micro-grid and depends on specific project characteristics, low voltage line losses, etc...

3.2 Resource and Demand Indicators

In order to evaluate the two characteristics previously identified (outstanding potential and surrounding energy demand concentration), a Resource and a Demand Indicator of a point *i* are hereby proposed. The proposed indicators are normalized by their maximum and minimum values in the community, so that they can be combined for *GGS*, *NGS* and *IGS* calculations.

3.2.1 Resource Indicator

As previously stated, the Resource Indicator (*RI*) should evaluate how much the potential of a point (reference point) outstands among the potential of the surrounding points. Considering a reference point *i*, potential differences with closest points should have a higher weight in comparison with potential differences with further points. Therefore, the relative potential of a point with respect to another could be calculated as the ratio between the potential difference and the distance between those 2 points. When considering a community, the Resource Indicator of a certain point *i* (RI_i^0, in equation (3.3)) is then the sum of the differences between HPI_i and HPI_j, considering all *j* points in a radius L_{max} around *i* (set N_i), divided by the distance L_{ij} between point *i* and *j*. In order to avoid unrealistic potential difference between really close points, e.g. resulting from uncertainties in GPS positioning or in the resource assessment procedure, a minimum distance L_{min} is established, so that all points closer that L_{min} to point *i* they are assumed to be at a distance L_{min}.

$$RI_i^0 = \sum_{j \in N_i} \frac{HPI_i - HPI_j}{\max\left(L_{ij}, L_{\min}\right)} \qquad (3.3)$$

Finally, the Resource Indicator RI_i is calculated normalizing RI_i^0 by its maximum and minimum vales in the community so that RI_i range is from -1 to 1. A positive RI_i value represents a point whose potential positively outstands between the surrenders while a negative value represents a point that negatively outstands.

3.2.2 Demand Indicator

The Demand Indicator (*DI*) of a point *i* evaluates the demand concentration around the point (including the demand of the own point). Similarly to the Resource Indicator, its value should be weighted for the distance from the reference point for which the indicator is evaluated. Therefore, the Demand Indicator (DI_i^0 in equation (3.4)) is calculated as the sum of the ratios between the energy demands ED_j of all the points in a radius L_{max} around *i* (set N_i) and the distance L_{ij} between point *i* and point *j*. As for the Resource Indicator, a minimum distance L_{min} is considered to avoid exaggerating the influence of points located at a too small distance.

$$DI_i^0 = \sum_{j \in N_i} \frac{ED_j}{\max\left(L_{ij}, L_{\min}\right)} \qquad (3.4)$$

Finally, the DI_i^0 is normalized by its maximum and minimum vales to obtain final Demand Indicator DI_i, whose value ranges from 0 to 1, being 0 the minimum and 1 the maximum value of the community.

3.3 Calculation of *GGS, NGS* and *IGS*

In the following, the calculation of the 3 specific indicators *GGS*, *NGS* and *IGS* that characterize the 3 types of points of an off-grid electrification projects is established. Development of equations for the calculation of those indicators are next analyzed and discussed.

3.3.1 Grid Generation Score

As previously stated (see Table 1), a micro-grid generation point should have a high potential in comparison with the surrounding points (positive Resource Indicator) and a high concentration of energy demand around it (high Demand Indicator). Therefore, the Grid Generation Score (*GGS*) should be in direct proportion with the Resource Indicator (*RI*) and with the Demand Indicator (*DI*). We propose the following 2 ways for the *GGS* calculation (equations (3.5) and (3.6)):

$$GGS_{i1} = \gamma \cdot RI_i + (1-\gamma) \cdot DI_i \qquad 0 < \gamma < 1 \qquad (3.5)$$

$$GGS_{i2} = (\alpha + RI_i) \cdot (\beta + DI_i) \qquad \alpha \geq 1, \beta \geq 0 \qquad (3.6)$$

Regarding equation (3.5), a sensitivity analysis has been carried out showing that small changes in the selection of the empirical coefficient γ considerably affect the GGS_1 value. Therefore, equation (3.5) has been discarded as that indicator is not stable.

When *RI* and *DI* are multiplied (equation (3.6)), *GGS* should take only positive values so that an increase in *DI* or *RI* means always an increase in *GGS*, therefore $\beta \geq 0$ and $\alpha \geq 1$. Assuming $\alpha = 1$, when the potential of a community is uniform (not variable in space) so that $RI = 0$, the *GGS* depends only on the Demand Indicator. With $\alpha = 1$ the point with the lowest Resource Indicator ($RI = -1$) has also the lowest *GGS* ($GGS = 0$), this is also a good assumption as it is clear that it will not be a good grid generation point.

Regarding β coefficient, a null β value means that the point *Y* with the minimum Demand Indicator has also a null *GGS*. This is not a good assumption, as the point *Y* could have a high RI_Y and therefore being a reliable grid generation point even if it located far from other demand points. Assuming $\alpha = 1$, a sensitivity analysis has been carried out with β varying from 0 to 1. In the range $0.3 \leq \beta \leq 0.7$, the GGS_2 is stable and a β value of 0.5 is proposed. Hence, final *GGS* equation could be rewritten as in equation (3.7).

$$GGS_i = (1 + RI_i) \cdot (0.5 + DI_i) \qquad (3.7)$$

3.3.2 No-Generation Score and Independent Generation Score

Hereby, the calculation of the *NGS* and *IGS* are discussed together and similar formulas for both indicators are proposed in order to make them easily comparable. In this manner, it is possible to evaluate which points are more suitable to be connected to a micro-grid and which should better be independent generation points.

As defined in Table 1, a No-Generation Point should have a low potential in comparison with the surrounding points (negative Resource Indicator) and a high demand concentration around the point (high Demand Indicator). On the other side, an Independent Generation Point should have a low demand concentration around it (low Demand Indicator) and a similar potential in comparison with the surrounding points (ideally null Resource Indicator). Neither the *NGS* nor the *IGS* should be then in direct proportion with both the *RI* and *DI*. Equations (3.8) and (3.9) are proposed for the calculations of the *NGS* and the *IGS* combining the Resource and Demand Indicators. A unit is added to both indicators so that *NGS* and *IGS* are always positive (minimum null). Therefore, *NGS* and *IGS* values could range from 0 to 2, as by equations (3.8) and (3.9). As the *RI* ranges from -1 to 1, in the *IGS* calculation the absolute value of *RI* is considered in order to evaluate how much its value moves away from 0 (the best situation).

$$NGS_i = 1 - \delta \cdot RI_i + (1-\delta) \cdot DI_i \qquad 0 < \delta < 1 \qquad (3.8)$$

$$IGS_i = 1 + \varepsilon \cdot (1 - |RI_i|) - (1-\varepsilon) \cdot DI_i \qquad 0 < \varepsilon < 1 \qquad (3.9)$$

Sensitivity analyses have shown that equations (3.8) and (3.9) are not particularly affected by the selection of δ and ε coefficients in the range between 0.2 and 0.8. In order to give the Resource and Demand Indicators similar weights a value of 0.5 is proposed for both δ and ε coefficients. Therefore final *NGS* and *IGS* equations could be rewritten as (3.10) and (3.11).

$$NGS_i = 1 - 0.5 \cdot RI_i + 0.5 \cdot DI_i \qquad (3.10)$$

$$IGS_i = 1 + 0.5 \cdot (1 - |RI_i|) - 0.5 \cdot DI_i \qquad (3.11)$$

4. Performance of the proposed indicators

The performance of the proposed indicators for the design of community electrification projects is analyzed in two real cases of mountainous communities: El Alumbre and Alto Peru. In this Section we described the analysis in detail of the indicators in El Alumbre community. As similar results and performance of the proposed indicators were obtained in Alto Peru (for the analysis of Alto Peru case study see Appendix A), El Alumbre case study is described in subsection 4.1 and values of the proposed indicators are calculated and analyzed in subsection 4.2. Finally, a simple heuristic based on the *GGS*, *NGS* and *IGS* is defined in subsection 4.3 and its results are compared with known optimal solutions.

4.1 Community description

Recently implemented rural electrification projects in the Andean sierra of Peru confirm the importance of considering micro-grids and hybrid generation in the design of community projects [27]. El Alumbre is a community composed of 33 households (380 Wh/day of energy demand each), a school and a health centre located in the centre of the community with a higher energy demand (1325 Wh/day each).

In Ferrer Marti et al. [14] the optimum solution that minimizes the installation cost of the electrification project has been encountered utilizing a Mixed-Integer Linear Programming (MILP) model. Wind and solar generation technologies are considered. MILP solution is shown in Figure 4. One central wind microgrid of 11 users is present in the MILP solution, while all the other households are independent users. The cost of the solution obtained by the model is $58674.

In MILP solution only demand points were considered as possible Grid Generation Points. This is common assumption in rural electrification projects for safety reasons, as it is preferable to have generators located close to houses. Then, in the calculation of the proposed indicators only demand points are considered so that results are comparable with MILP solutions.

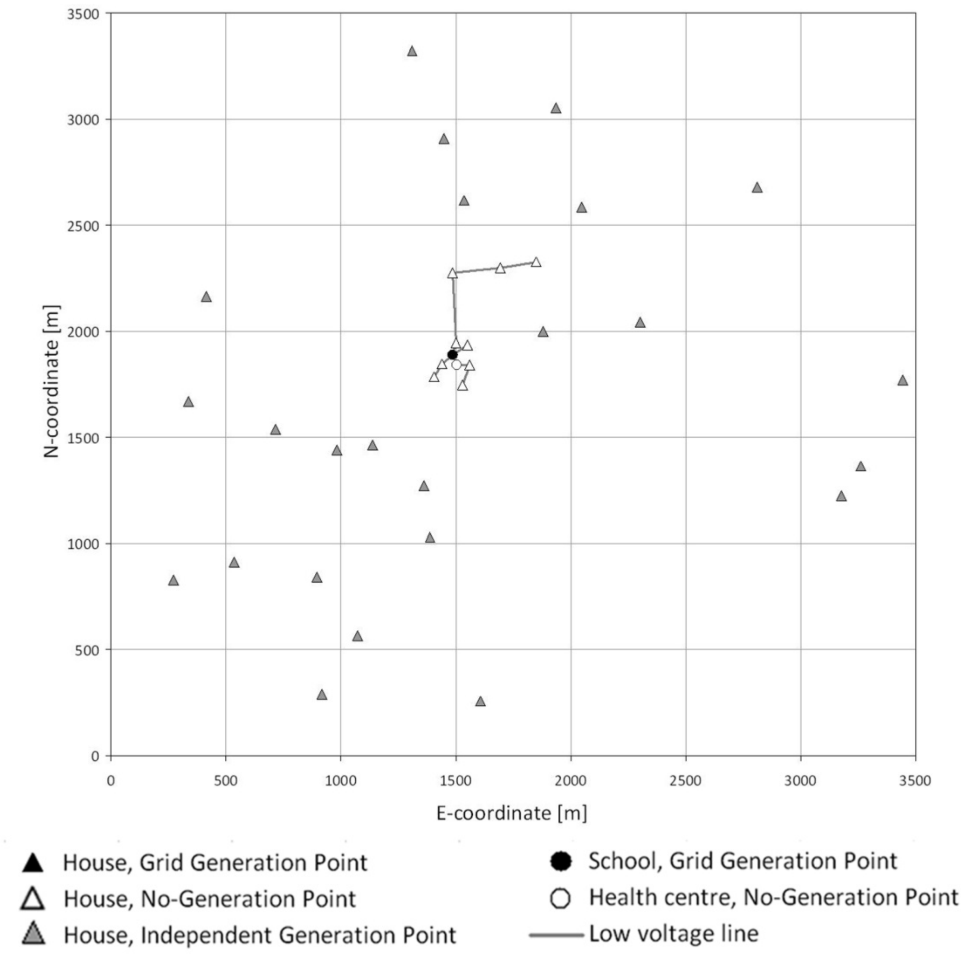

Figure 4 – Optimal design configuration in El Alumbre [14]

4.2 Proposed indicators analysis

The Resource Indicator (*RI*) and the Demand Indicator (*DI*) values for all the users in the community of El Alumbre are shown in Figure 5. Circles areas are proportional to their *RI* or *DI* values. Positive values of *RI* are shown by grey circles while white circles means a negative *RI*. In both communities a maximum radius L_{max} of 2000 m and a minimum distance L_{min} of 50 m have been considered for the calculation of *RI* and *DI*. The Resource Indicator of the central points takes minimal or negative values as they are surrounded by points that have a higher potential and therefore a positive *RI* (maxima *RI* values in points 1 and 2 of Figure 5). The Demand Indicator shows maxima values for the 8 points located very close to each other in the centre of the map and it decreases as moving away from them.

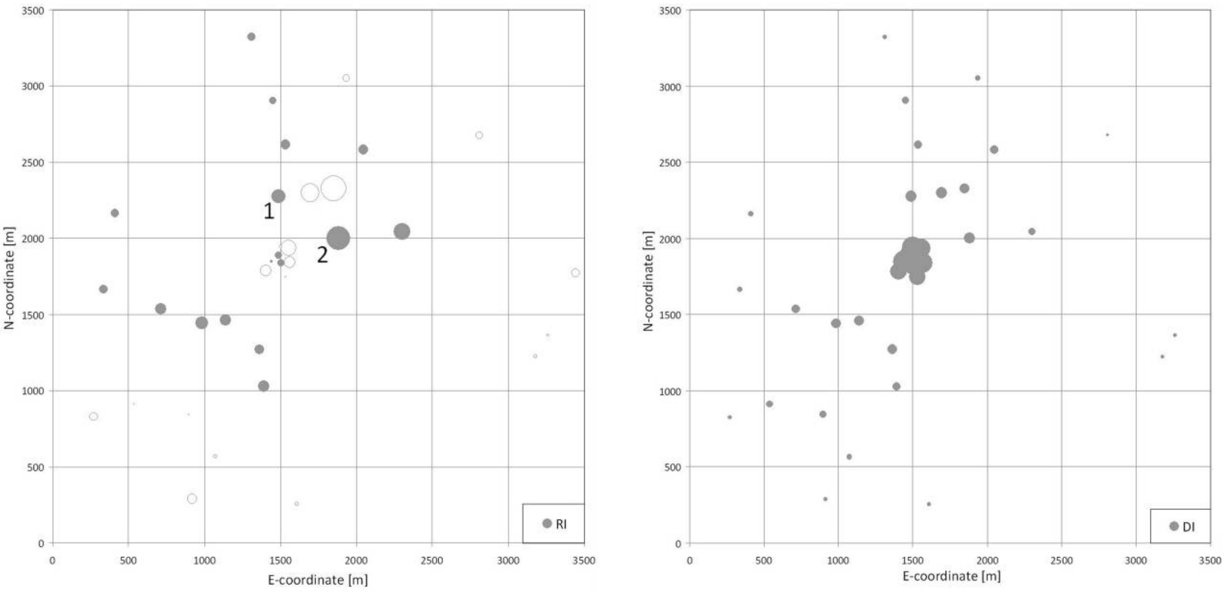

Figure 5 – Resource Indicator (*RI*) and Demand Indicator (*DI*) in the community of El Alumbre.

Figure 6 shows the user with the highest *GGS* value (dark circle) and the difference between *IGS* and *NGS* for the rest of the demand points. Grey filled circles mean a positive value of the difference (*IGS>NGS)*, while white filled circles mean a negative value (*IGS< NGS)*. The point with maximum *GGS* is the school and coincides with the micro-grid generation point of the optimal solution. The 7 points located in the centre surrounding the school have a No-Generation Score higher than the Independent Generation Score, as the 2 houses located in the north-east of the centre.

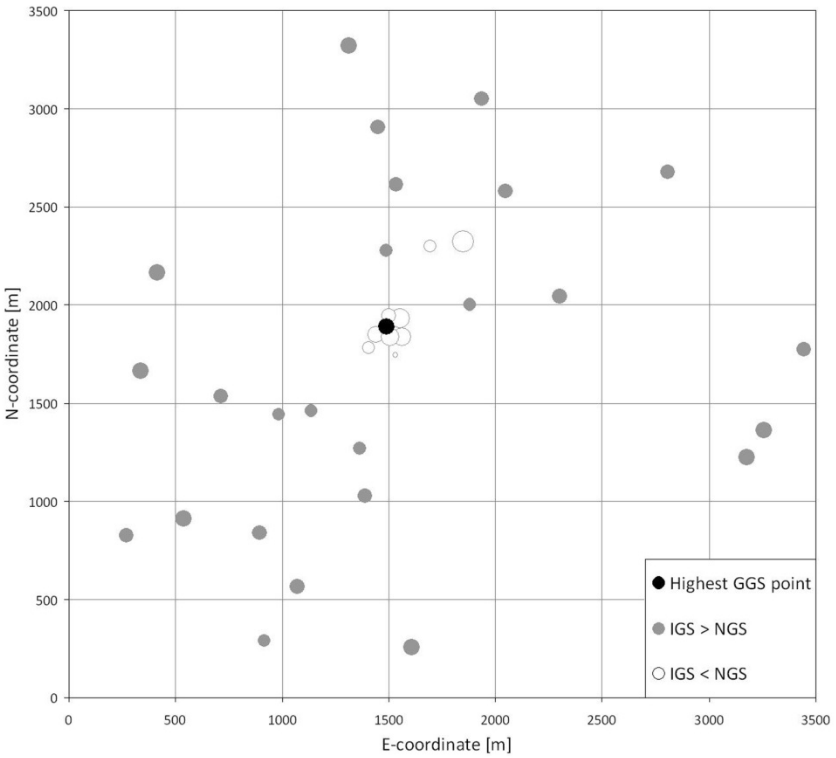

Figure 6 –Point with highest *GGS* value and differences between *IGS* and *NGS* values for the rest of demand points in El Alumbre community.

4.3 A simple heuristic procedure based on *GGS, NGS* and *IGS*

To test the proposed heuristic indicators the authors will apply a simple algorithm. More elaborate procedures will be carried out in future studies. This algorithm shows how a good solution could be quickly obtained by directly utilizing *GGS*, *NGS* and *IGS* values. The procedure considers the design of a single radial micro-grid, which is a typical assumption in rural electrification projects [20, 17].

The algorithm consists of the following three steps:

1) Selection of grid generation point *X* as the point with maximum *GGS* between the whole community.
2) Demand points that have the *NGS* value higher than the *IGS* are connected to the micro-grid with generation in *X*. Micro-grid is designed utilizing the shortest connection network algorithm [28] in order to minimize cable length.
3) Demand points that have the *IGS* value higher (or equal) than the *NGS* are considered as independent generation points in the solution.

The algorithm has been applied in El Alumbre community and results are compared with the optimal solution. Same input data as in Ferrer-Martí et al. [14] are utilized. The solution obtained by the proposed algorithm with a calculation time of less than 1 minute (Figure 7) is similar to the optimal solutions obtained by the MILP model with a calculation time of 5 hours (Figure 4). The only difference with respect to the optimal solution is that point 1 of Figure 7 is not connected to the micro-grid. In fact, this point has a relatively high Resource Indicator (Figure 5) and therefore its *NGS* is low.

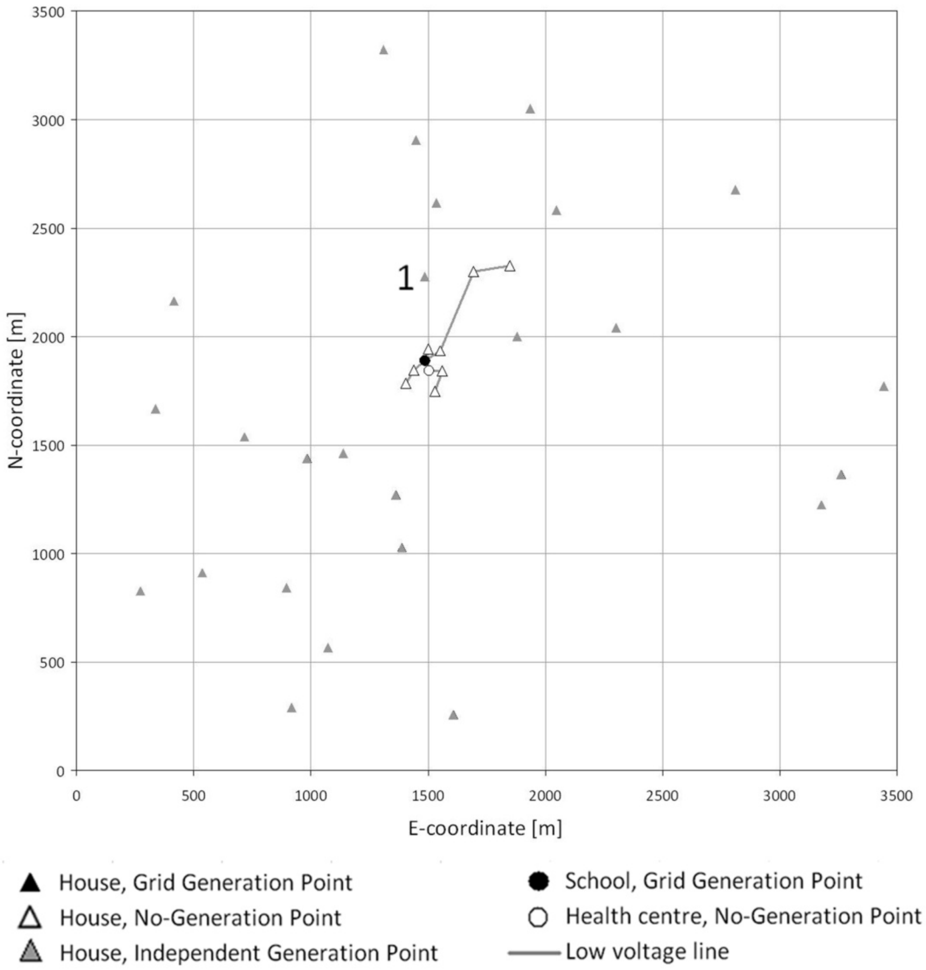

Figure 7 –Solution obtained in El Alumbre by the proposed heuristic

Table 2 compares the costs of the optimal solution [14] and of the solution obtained by the heuristic algorithm ($59437). On the other side, it should be noted that the real project was designed relying only on promoter experience and no model was implemented in order to support the design; its cost is also shown in Table 2. Resulting costs difference is minimal (around 1%) between the optimal and the heuristic solutions. As reported in Appendix A (Table A.1), similar results were obtained in Alto Peru with a difference of 2.5% between optimal and heuristic solutions. Furthermore, the fast solutions obtained by the heuristic based on *GGS*, *NGS* and *IGS* values reduce real project costs of more that 20% in both communities.

Table 2 – Costs' comparison (in $) between optimal and proposed heuristic solutions in El Alumbre. Real cost of the electrification project [14] is also visualized

	El Alumbre
Optimal solution cost (Figure 4)	58674
Proposed heuristic solution cost (Figure 7)	59437
Difference (optimal - heuristic solution)	1.2%
Real project cost (only wind energy)	75517
Difference (heuristic solution – real project)	21%

Even if the proposed heuristic is simple, the results show that reliable design solutions could be obtained by directly utilizing the *GGS*, *NGS* and *IGS*. The proposed indicators could be therefore usefully applied in decision support tools in order to improve the design of off-grid rural electrification projects based on renewable energies. Furthermore, the *GGS* could be utilized a-priori in order to select most promising no-demand points to be considered as possible Grid Generation Points by the MILP model. Indeed, the MILP model [14] that currently considers only demand point locations as possible generation sites could not include all no-demand points as their number is theoretically infinite and computational time will then be not viable. The identification of a limited number of no-demand points as possible grid-generation points by the use of the *GGS* will facilitate designing projects with the MILP model considering generation far away from the consumption.

5. Conclusions

In off-grid rural electrification project, configurations that consider hybrid systems and the implementation of micro-grids are the most promising design solutions. Their utilization can lead to a decrease in installation costs and an increase in supply quality. Despite the complexity of the design of these systems, computational and optimization software resources available to rural electrification promoters are generally limited and a fast solution is generally preferred.

This study proposes indicators for supporting the design of community electrification projects considering hybrid generation and microgrids. The Grid Generation Score (*GGS*) identifies most promising locations for being the generation point of a micro-grid connecting multiple demand points. The No-Generation Score (*NGS*) and the Independent Generation Score (*IGS*) evaluate if a point should be reliably connected to a micro-grid or should better be an independent generation point. All proposed indicators could be easily and quickly calculated (even on small portable computers) at a very first stage of the design of a community project requiring as input data only demand and resource distributions in the studied area. A simple procedure based on the proposed indictors in order to obtain fast solutions with a single micro-grid is finally presented and tested in two real mountainous communities in Peru. Solutions obtained are similar to optimal solutions encountered in literature.

The utilization of the proposed indicators can enhance the design of stand-alone community electrification projects, helping to overcome some of the technical barriers that still limit the diffusion of those projects, such as the requirements of easy, fast and no-computationally complex design approaches. They can be used as a starting point or a support tool in other optimization models or directly as a design criterion of electrification projects. In this study, a simple heuristic method is described; but, as future research, the design of more complex heuristics based on the proposed indicators will be studied in order to improve its performance. Furthermore, *GGS* performance in selecting most relevant no-demand points as possible grid generation points (that could be ideally every point of a certain area) will be analyzed in future works.

Acknowledgements

This paper was supported by the Spanish Ministry of Education (FPU grant AP2009-0738), the MICINN project ENE2010-15509, co-financed by FEDER and by the Centre for Development Cooperation of the Technical University of Catalonia.

Appendix A – Alto Peru community study

In Alto Peru there are 26 households with energy demand of 240 Wh/day each. The optimal solution of Ferrer-Martí et al. [14] shows a central micro-grid with wind generation of 13 users, 2 solar small micro-grids of 2 users each and the rest are solar independent users (Figure A.1). The cost of the solution obtained by the model is $35843.

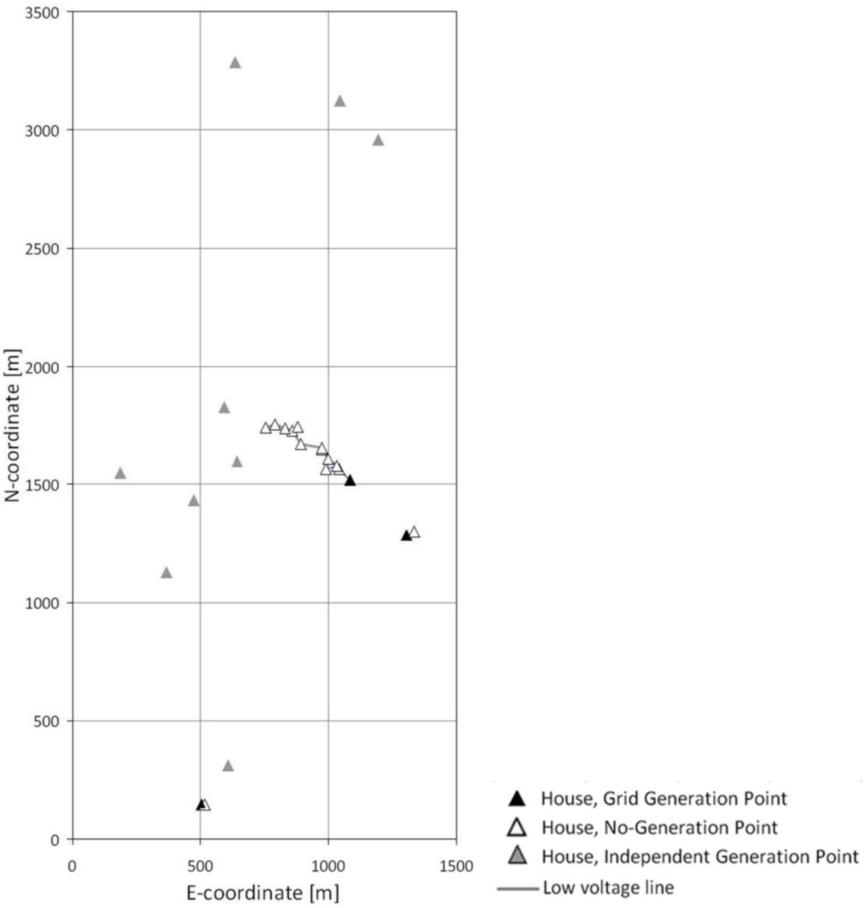

Figure A.1 – Optimal design configuration in Alto Peru [14]

The Resource Indicator (*RI*) and the Demand Indicator (*DI*) values for all the users are shown in Figure A.2. The point with highest potential between all central points has the highest *RI*. Positive *RI* values are also encountered for the 2 houses on the eastern part of the map that have a really high and similar potential; the rest of community points have a null or negative *RI*. The *DI* is clearly higher for the points located in the central concentration of the community in comparison with points located further away.

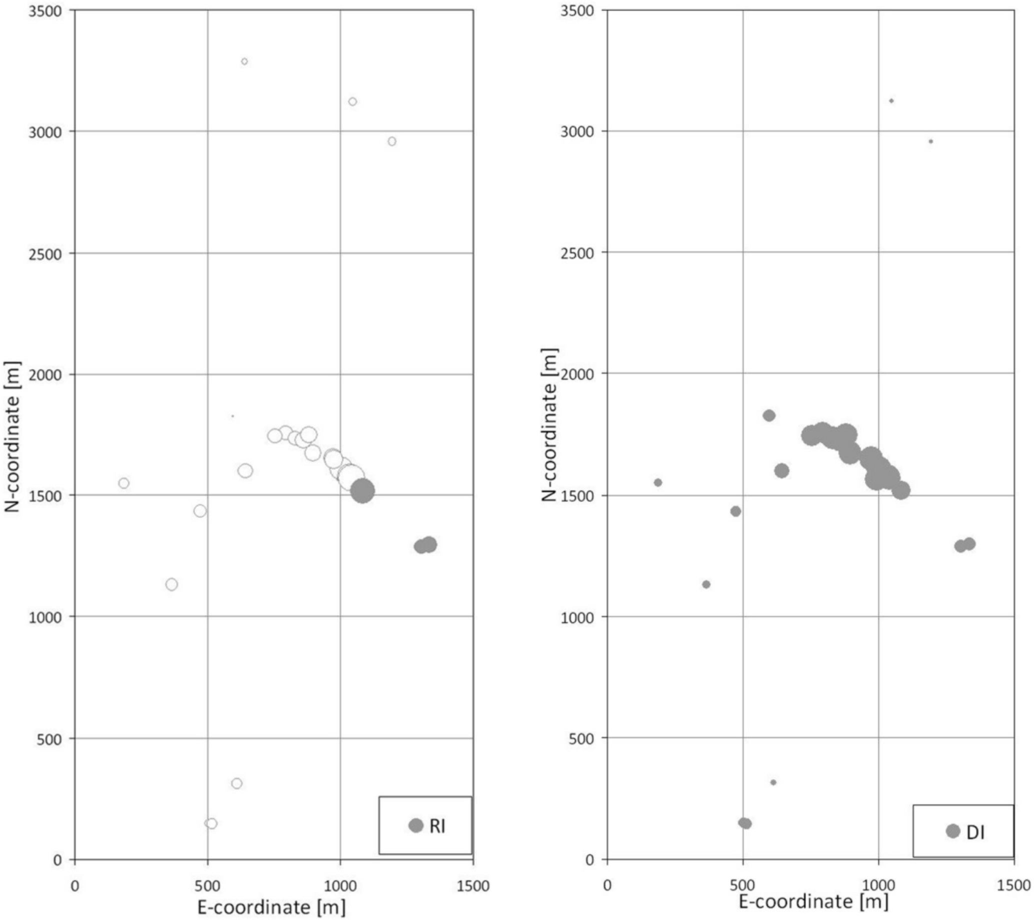

Figure A.2 – Resource Indicator (*RI*) and Demand Indicator (*DI*) in the community of Alto Peru.

Figure A.3 shows on the left the user with the highest *GGS* value (dark circle) and the difference between *IGS* and *NGS* for the rest of the demand points, on the right the solution obtained by the algorithm described in sub-Section 4.3.

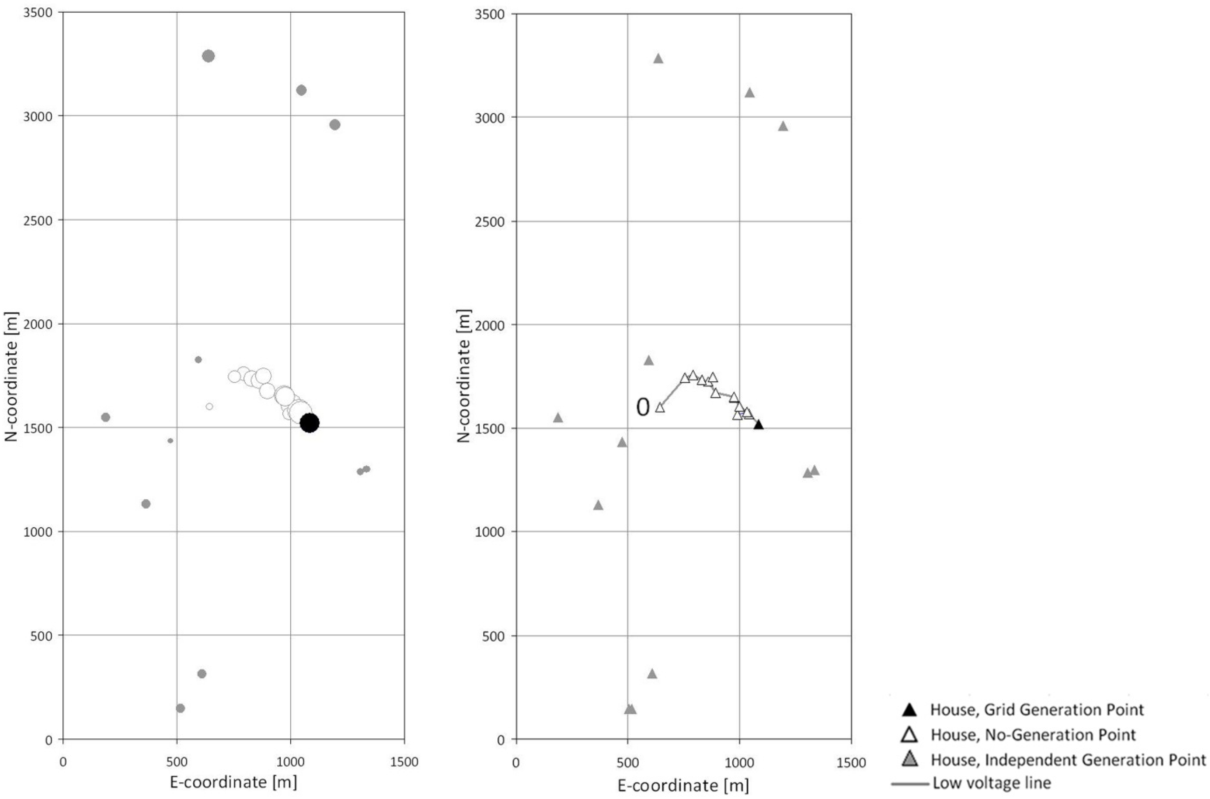

Figure A.3 – Point with highest *GGS* value and differences between *IGS* and *NGS* values for the rest of demand points in Alto Peru (left) and solution obtained by the proposed heuristic (right)

As in El Alumbre, the solution obtained in Alto Peru by the proposed algorithm with a calculation time of less than 1 minute (Figure A.3 right) is similar to the optimal solution obtained by the MILP model in 5 hours (Figure A.1). The central micro-grid corresponds really well with the optimal one; just one point located slightly on the west of the centre (point 0 in Figure A.3) is added to the micro-grid. The two small micro-grid located in the southern and eastern part of the map in the MILP solution are not present in the solution encountered by the heuristic, as a single micro-grid could only be designed by the heuristic. Due to their small size (only connecting 2 users each), their effect on the project cost is small, see Table A.1. The costs difference is around 2.5% between the optimal and the heuristic ($36735) solutions (Table A.1).

Table A.1 – Costs' comparison (in $) between optimal and proposed heuristic solutions in Alto Perú. Real cost of the electrification project [14] is also visualized

	Alto Peru
Optimal solution cost (Figure A.1)	35843
Proposed heuristic solution cost (Figure A.3)	36735
Difference (optimal - heuristic solution)	2.5%
Real project cost (only wind energy)	51691
Difference (heuristic solution – real project)	29%

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A heuristic method to design autonomous village electrification projects with renewable energies

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Article published as [Ranaboldo M, García-Villoria A, Ferrer-Martí L, Pastor Moreno R. A heuristic method to design autonomous village electrification projects with renewable energies. Energy 2014; 73: 96-109] © [copyright Elsevier]

Abstract

Systems relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously. Hybrid systems that combine different energy resources and distribution microgrids are the most efficient design configurations. The design of these systems requires the use of decision support tools, while projects' promoters generally dispose of low design resources. This study presents a heuristic method to design off-grid electrification projects based on wind and solar energies considering micro-scale resource variations and a combination of independent generation points and microgrids. The method considers generation far from users and a pre-selection process is presented in order to screen the initial pool of potentially infinite generation points. Different algorithm versions are evaluated and performances are compared with existing tools: VIPOR, known software for microgrids design, and a recently developed mixed integer linear programming (MILP) model. The proposed heuristic performs better than VIPOR with mean improvements of around 6% and, for communities of more than 40 users, considerably enhances solutions obtained by the MILP model with a much lower computational time (1 minute against 1 hour). The method is a complete and simple tool that can efficiently support the design of stand-alone community electrification projects with renewable energies.

Nomenclature

- Demand point (or user): location of a consumption point, such as a house or a public building, with certain energy and power demands.
- Community: a group of users.
- No-demand point: location (that is not a demand point) where it is possible to install generators.
- Microgrid: set of demand points fed by a generation system placed in a demand or no-demand point.
- Arch: segment of electric cable that connects 2 points of a microgrid.
- Solution: set of microgrids.

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1. Introduction

Over the last decades, systems relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously [1, 2]. These systems produce electricity in a clean way, their cost is often lower than national grid extension and they are not dependent from external resources, therefore increasing projects long-term sustainability [2]. In particular, systems relying on wind and solar energies are one the most promising electricity generation options [3]. When designing rural electrification projects based on renewable energies various issues should be taken into account for the correct operation of the systems, especially the variability of the renewable resources and the dispersion of the energy demand that depends on houses locations. In particular, wind resource is the most scattered and significant resource variations can be encountered within the same community in mountainous areas [4].

In this context, the configurations that proved to be the most reliable design options are hybrid systems that combine different generation resources [3, 5] and distribution microgrids, where the energy is produced in a certain point and distributed through an electric grid to other consumption points [6, 7]. Hybrid systems improve the system efficiency and reliability of the energy supply and reduce the energy storage requirements compared to systems comprising only one single renewable energy resource [5]. Distribution through microgrids could lead to an important decrease in the final cost of the system in comparison with independent generation points, i.e. a demand point that generates energy just for its own consumption, and enhance the flexibility of the system [6, 7]. However, in scattered communities with isolated users the combination of independent generation points and microgrids is generally the cheaper design solution [8].

When considering hybrid systems and distribution microgrids, the complexity of the design increases and requires the use of optimization/decision support tools [9]. Many tools have been developed in recent years in order to define the best combination of energy resources in one point but without designing the distribution through microgrids [5, 9, 10, 11, 12, 13] and several software tools are available for designing hybrid systems, such as HOGA, HOMER and HYBRID2 [14]. These tools are currently applied for the design of different projects all around the world [15, 16, 17]. On the other side, just few studies focus on the design of off-grid electrification systems taking into account hybrid systems and the design of microgrids [18, 19].

Ref. [18] developed a mixed integer liner programming (MILP) model that optimizes the design and localization of microgrids, wind turbines and solar panels defining all electric equipments to be installed, taking into account voltage drops along the cables and wind resource variability. The model assumes that generation points must be located close to the users. It has been efficiently used to design off-grid electrification projects in Peru [18] and Cape Verde [20]. However, due to its high computational requirements, the application of the mathematical model may be unreliable when the size of analyzed community (e.g. the number of demand points) increases. Furthermore, recent studies have shown that considering generation far from demand points could substantially decrease initial investment costs taking advantage of best resource areas [20, 21]. Therefore, the generation point could be potentially every point in a certain area, further significantly increasing problem complexity.

It should be noted that promoters of rural electrification projects generally dispose of low resources for project design, making it preferable to use simple and fast tools in order to support the design [22]. At the same time, different project configurations should be preferably evaluated in order to take into account not only technical aspects but also social aspects specific of each community [23]. In this context, heuristic methods (or simply "heuristics") are a technique commonly used in combinatorial optimization problems [24] in order to accelerate the solving procedure or to make viable the solution to problems that cannot currently be optimally solved even by super-computers. Heuristics will generally not guarantee the optimal solution but, when well designed, the obtained solutions can be expected to be fairly close to the optimum value [25].

As resulted from literature analysis, the only heuristic method for the design of off-grid electrification projects considering microgrids, hybrid generation systems and resource spatial variations is VIPOR [19, 26]. VIPOR designs the distribution system (electric cables) and where generation should be located but does not define the number of equipments required for generation (generation system). Other drawbacks of VIPOR, that reduce its range of application, are the limited pool size (10 as maximum) of possible grid generation points, the no-consideration of some electrical constraints, such as the voltage drop, and the assumption of a uniform resource in the area for independent generation points.

Recently, some indicators have been proposed to support the design of off-grid community electrification projects [27]. The indicators could be used to select most promising generation points in a certain area and to heuristically evaluate how much some a-priori characteristics of a point indicate that it should be reliably connected to a microgrid or should be an independent generation point producing energy just for its own consumption [27]. A simple heuristic procedure in order to obtain fast solutions with a single microgrid is also presented in ref. [27].

In this study we present a heuristic method to design community off-grid electrification projects based on wind and solar energies considering micro-scale resource variations and a combination of independent generation points and microgrids. Unlike existing tools, generators locations are not forced to be close to demand points and their number is not limited, therefore a generation point could be potentially every point in the studied area. The indicators described in ref. [27] are used in order to design the heuristic algorithm. The performance of the proposed method aims to overcome the performance of currently available heuristics [19, 27]. The results of the heuristics are also compared with the solutions obtained by the MILP model [18].

The rest of the paper is organized as follows. Section 2 presents the components of a general off-grid electrification project and the problem to be solved. The heuristic algorithm is described in detail in Section 3 and in Section 4 the performances of the proposed heuristic are compared with existing procedures. Section 5 deals with the conclusions.

2. Autonomous village electrification project design: problem statement

In this Section the problem to be solved (i.e. the design of an off-grid community electrification project with wind and solar energies) is defined. Firstly the input data are described (sub-Section 2.1), the components of a hybrid off-grid electrification system are resumed (sub-Section 2.2) and finally the objective function and constraints of the problem are defined (sub-Section 2.3).

2.1 Input data

Input data for an off-grid electrification project design could be generally divided into three types: social, technical and energy data of the community.

The characteristics resulting from the social evaluation are the following:

- Users' position;
- Electrical energy and power demand of each user.

The technical and energy characteristics are the following:

- Resource available in the area (i.e. daily energy production with all types of generators in every possible generation point);
- Technical data of generation, storage, control and distribution equipments;
- Costs of all the equipments.

The involved area in an off-grid electrification project is generally between 1x1 till 10x10 km^2 and the number of households of a community is generally between 10 and 100 users [7, 28]. Wind resource could vary considerably within the area of a community, especially in mountainous areas [4], while the solar resource is generally considered uniform at this scale [29].

2.2 Components of an off-grid electrification system

The scheme of the elements involved in a wind - photovoltaic autonomous electrification system is as follows (Fig. 1):

1) Generators: produce energy in alternating (wind turbines) or direct (solar panels) current.
2) Controllers: convert current and control the charge/discharge of the batteries.
3) Batteries: store the energy produced by the generators, receive and supply electricity at direct current (DC).
4) Inverters: convert direct to alternating current (AC) at the nominal voltage.
5) Electric cables: configure the microgrid that distributes the energy (only low voltage distribution is considered).
6) Electric meters: measure the energy consumed at the demand points.
7) Users (or Demand points): consume the energy.

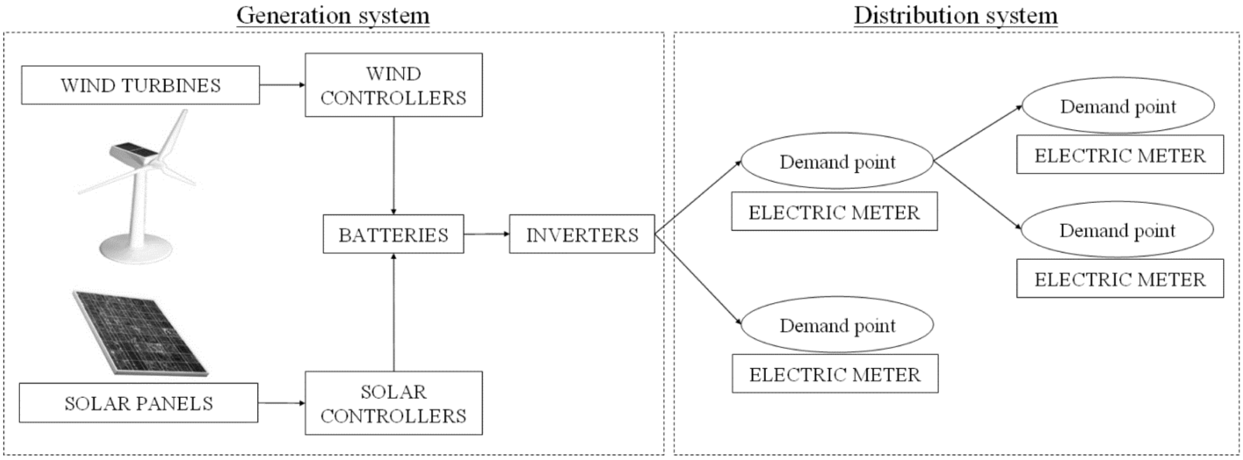

Figure 1 – Scheme of the elements involved in a hybrid wind-photovoltaic electrification system.

A generation system (or generation point) is composed by the generators (wind turbines and solars panels), controllers, batteries and inverters. The energy produced by a generation system is distributed to the users via "microgrids", connecting users with electric cables (distribution system). The radial microgrid configuration (i.e. a single generation point and distribution in form of a tree as in Fig. 1) is generally the preferred one in rural electrification projects [19, 30]. The radial microgrid configuration is then considered in this study.

2.3 Objective function and constraints of the problem

The design of an off-grid electrification project using local available resources and a combination of independent generation points and microgrids is a hard combinatorial optimization problem [8]. The aim is to find the lowest cost configuration (generation points' locations and microgrids design) that accomplish with the energy and power demands of each user, taking into account energy resource maps and different technical constraints. For sake of simplicity, this problem will be referred to as the Autonomous Village Electrification through Renewable Energy and Microgrid Systems (AVEREMS) design problem. The complete mathematical formulation of a MILP model for solving the AVEREMS problem is presented in ref. [18] and reported in Appendix A. Next, the objective function of the problem and the main constraints of the generation and distribution systems (Fig. 1) are resumed:

o Objective function: To minimize the initial investment of the project, as this is generally the principal interest in these projects [31]. Costs of all equipments defined in Fig. 1 are considered, i.e. wind turbines, wind controllers, PV panels, solar controllers, batteries, inverters, meters, and cables.

o Constraint of both the *generation* and the *distribution systems*:

- The conditions of conservation and satisfaction of the energy (and power) demand are imposed; i.e. the energy (power) arriving at a point *p* plus the energy (power) generated at the own *p* must be higher or equal than the energy (power) consumed by *p* plus the energy (power) leaving *p*. This constraint takes into account batteries and inverters efficiencies for the energy conservation and cables efficiency for both energy and power conservations.

o Constraints of the *generation system*:

- A maximum number of wind turbines or PV panels can be installed in the same generation point.
- Controllers, batteries and inverters must be installed in generation points.
- Wind (and solar) controllers must be adequately powered according to the wind turbines (and PV panels) installed at the same point.
- Batteries are forced to store enough energy to cover the demand of the supplied users, considering the required days of autonomy and the maximum discharge.
- Inverters type and quantity are determined according to users power demand.

o Constraints of the *distribution system*:

- Every demand point of a microgrid must be connected to the generation system by an electric cable.
- The condition of radial scheme of the microgrids is imposed: each point can have, at the most, one input wire except for the generation points that cannot have any.
- The voltage drop in a microgrid is calculated according to formulas recommended in ref. [32]. The maximum voltage drop must be satisfied in every node of the microgrid considering cable electric resistance.
- The intensity flowing between two points connected by a cable cannot be higher than the maximum admissible intensity of the cable utilized.

An example of a possible solution to the AVEREMS problem for the community of El Alumbre (Peru), described in ref. [8], is shown in Figure 2.

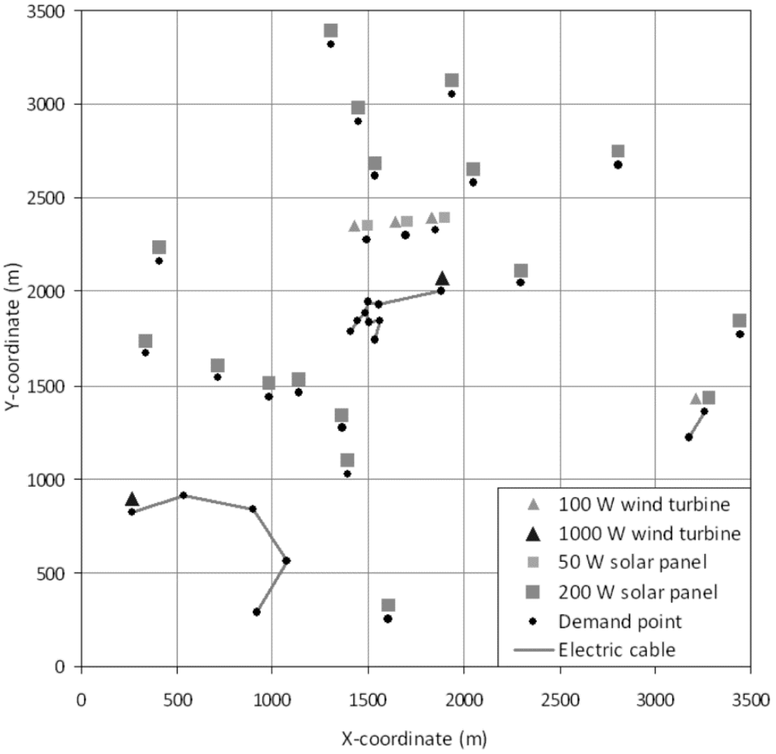

Figure 2 – Possible solution to the AVEREMS problem in the community El Alumbre considering individual generation points and microgrids

3. Heuristic description

As previously stated, low resources are usually available for rural electrification projects' design while different configurations should preferably be evaluated [22, 33]. In this sense, the main idea of the heuristic algorithm hereby proposed is to dispose of a simple and fast tool that could be easily used by promoters to support the design of those projects even in big rural communities (e.g. more than 50 users).

Recently, the following indicators have been proposed [27] as a tool to support the design of off-grid electrification projects with renewable energies:

- The Hybrid Potential Indicator (*HPI*) evaluates the resource available in a point considering multiple renewable energy resources (such as wind and solar).
- The Grid Generation Score (*GGS*) evaluates how much some a-priori characteristics of a point indicate that it should be the generation point of a radial microgrid connecting multiple demand points.
- The No-Generation Score (*NGS*) evaluates how much some a-priori characteristics of a point indicate that it should be connected to a microgrid and just consuming energy.
- The Independent Generation Score (*IGS*) evaluates how much some a-priori characteristics of a point indicate that it should be an independent generation point producing energy just for its own consumption.

Relying on the use of those indicators, we propose a greedy heuristic that aims to obtain a fast and good solution to the AVEREMS problem without requiring of high computational resources. The proposed heuristic main structure is composed by 2 phases, as shown in Figure 3:

1) Construction
2) Local optimization

The "construction phase" refers to the construction of an initial solution. In this phase, the solution considering all independent generation points is firstly calculated, then the algorithm tries to extend microgrids as much as possible, according to the cost criterion. The "local optimization phase" is composed by 2 steps that are repeated if they improve previously obtained solution: firstly the microgrids are divided (if this brings to a better solution) into smaller ones and then the resulting microgrids are tried to be interconnected between them. Therefore the whole heuristic can be seen as a multiple steps process in which microgrids expansion and microgrids reduction are subsequently carried out till no further improvements are obtained (Figure 3). It should be noted that, in order to facilitate heuristic description and comprehension, an independent generation point is considered as a microgrid composed by a single user.

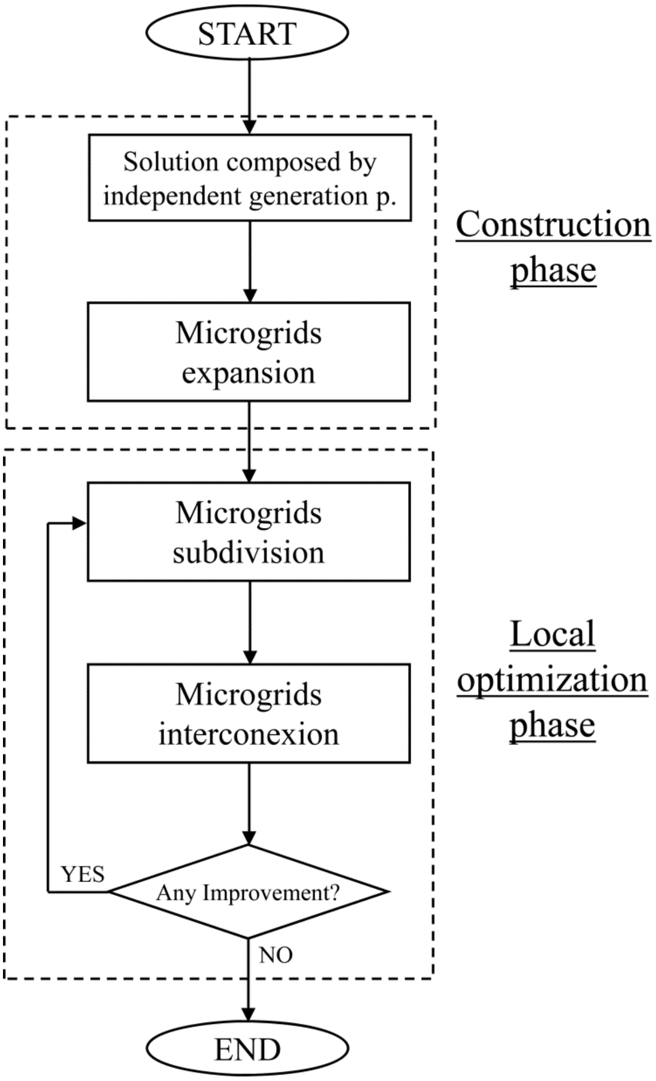

Figure 3 – Algorithm main structure

The AVEREMS problem has some similarities with the Plant Location Problem (PLP) which is one of the most studied themes in the field of Operations Research [34]. The basic statement of the PLP is: given a set of clients' locations with a given demand of a product and a set of possible plants' locations, find the number and location of plants to be opened and connections to be constructed in order to cover clients' demand with minimum installation (setup) and transport costs [34]. When each potential plant (equivalent to solar panels and wind turbines) has a capacity, that is, an upper bound, on the amount of demand that it can service, the problem is known as the capacitated plant location problem (CPLP). It should be noted the microgrids expansion and reduction steps are conceptually similar to the ADD and DROP procedures (for a detailed description of those two methods see ref. [35]) that have been widely applied in solving the CPLP: a combination of those procedures resulted to be a very efficient heuristic solution method.

Next, in sub-section 3.1 the internal functions used to define the proposed heuristic are presented. A pre-selection process is described in sub-section 3.2 in order to screen the initial pool of possible generation points (potentially infinite). Then the heuristic algorithm is described in detail in sub-Sections 3.3 (construction phase) and 3.4 (local optimization phase).

3.1 Internal functions used in algorithm description

The internal functions used by the heuristic algorithm are hereby reported.

HPI(*x*)	Hybrid Potential Indicator of point *x* [27], being *x* a demand or a no-demand point
GGS(*x*)[1]	Grid Generation Score of point *x* [27], being *x* a demand or a no-demand point
NGS(*x*)[1]	No-Generation Score of point *x* [27], being *x* a demand point
IGS(*x*)[1]	Independent Generation Score of point *x* [27], being *x* a demand point
P(*m*)	Set of points of microgrid *m*
MS(*s*)	Set of microgrids of solution *s*
S(*M*)	Solution composed by microgrids of set *M*
MP(*s, x*)[2]	Microgrid (part of solution *s*) at which belongs point *x*
R(*m*)[2]	Generation point (root) of microgrid *m*
MR(*m,x*)[2]	Microgrid (composed of *P*(*m*) points) imposing generation in point *x*. Then, *x* is the root of microgrid *m*
C(*m*)[2]	Cost of microgrid *m*, including generation, storage and distribution costs. The cost of the microgrid is calculated according to ref. [18] given the root and the connections of the microgrid.
C(*s*)	Cost of solution *s*. $C(s)=\sum_{m\in MS(s)} C(m)$
MU(*m1,m2, r*)	Microgrid (*MU*) that results after connecting all demand points of microgrids *m1* and *m2*. The root of microgrid *MU* depends on the binary parameter *r*. If *r* = false (utilized in the construction phase: *R(MU)* is preferably *R*(*m1*); *R*(*m2*) is selected only if it leads to a lower microgrid cost and has a *HPI* higher than *R*(*m1*)): if *C*(*MR*(*MU,R*(*m2*))) < *C*(*MR*(*MU,R*(*m1*))) and *HPI* (*R*(*m2*)) > *HPI* (*R*(*m1*)) then *R*(*MU*) = *R*(*m2*) otherwise *R*(*MU*) = *R*(*m1*). If *r* = true (utilized in the interconnection step of the local optimization phase): if *C*(*MR*(*MU,R*(*m2*))) < *C*(*MR*(*MU,R*(*m1*))) then *R*(*MU*) = *R*(*m2*) otherwise *R*(*MU*) = *R*(*m1*).
A(*m*)	Set of arches of microgrid *m* sorted by their cost in descending order
L(*x,y*)	Distance between point *x* and *y*
L(*x,a*)	Distance between point *x* and arch *a* (calculated as the minimum distance between a point and a line).
L(*x,m*)[3]	Distance between point *x* and microgrid *m* If |P(*m*)| = 1 then *L*(*x,m*) = *L* (*x,R*(*m*)) else $L(x,m)=\min_{a\in A(m)} L(x,a)$
L(*m1,m2*)[3]	Distance between microgrids *m1* and *m2*. $L(m1,m2)=\min\left(\min_{x\in P(m1)} L\left(x,m2\right),\ \min_{x\in P(m2)} L\left(x,m1\right)\right)$
BED(m)	Break Even Distance (*BED*) of microgrid *m*. It is a concept used in off-grid electrification projects in order to decide whether to connect a certain community to the national grid [37]. Hereby, it represents the maximum distance at which microgrid *m* could be reliably connected to another

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[1] The *GGS*, *NGS* and *IGS* values depend on the number of demand points considered in their calculation. Their value could be considered constant (static) or variable as a function of the number of considered demand points (dynamic). This issue is discussed in Section 3.3.

[2] Given the root and the points part of a microgrid, cable connections between them follow a radial tree-scheme and their length is minimized using the classical shortest connection network algorithm [36].

[3] The length of the electric cable extension in order to connect 2 microgrids (or a point and a microgrid) is better approximated by the minimum distance between the arches of the microgrids than by the minimum distance between the points of the microgrids. That is why the distance between 2 microgrids is defined as the distance between the arches of both.

microgrid or to a no-demand generation point. Given *UCC* the lowest unitary cable cost [$/m] and *CC*(*m*) the total electric cable cost of microgrid *m*, $BED(m)=\dfrac{C(m)-CC(m)}{UCC}$

MD(*a,m*) Set of 2 microgrids ($MD_1(a,m)$, $MD_2(a,m)$) resulting from removing arch *a* of microgrid *m*.
$R(MD_1(a,m)) = R(m)$;
$$R\left(MD_2(a,m)\right)=\underset{x\in P(MD_2(a,m))}{\operatorname{argmin}}\left(C\left(MR\left(MD_2\left(a,m\right),x\right)\right)\right)$$

Split(*m*) Set of (1 or 2) microgrids that results after trying to eliminate one by one all arches of *m*. The function stops when a division is accepted because the cost is reduced. If no division is accepted then the function returns *m*. The algorithm of this function is reported in the following.

```
For ($a \in A(m)$)
  If $C(MD_1(a,m)) + C(MD_2(a,m)) < C(m)$ then
    return $\{MD_1(a,m), MD_2(a,m)\}$
  EndIf
EndFor
return $m$
```

SelectP(*m,P, s*)[4] Returns the point *pc* to be connected to microgrid *m*. *s* is a solution and *P* is the set of points from which *pc* is selected. The point *pc* could be selected in the following 3 different ways (where $m_x = MP(s, x)$):

1. By distance: $pc=\underset{x\in P|L(x,m)\le BED(m_x)}{\arg\min} L\left(x,m\right)$
2. By *NGS*, *IGS* and distance: $pc=\underset{x\in P|L(x,m)\le BED(m_x)}{\arg\max}\left(\dfrac{1+NGS(x)-IGS(x)}{L(x,m)}\right)$
3. By savings:

$$pc=\underset{x\in P|L(x,m)\le BED(m_x)}{\arg\max}\left(\left(C(m)+C\left(m_x\right)\right)-C\left(MU\left(m,m_x,\text{false}\right)\right)\right)$$

SelectM(*m, M*) Returns the microgrid *mc* to be connected to microgrid *m*. *mc* is selected from set *M* of microgrids. The selected microgrid *mc* is

$$mc=\underset{z\in M|L(z,m)\le max(BED(z),BED(m))}{\arg\max}\left(\left(C\left(m\right)+C\left(z\right)\right)-C\left(MU\left(m,z,\text{true}\right)\right)\right)$$

E(*i, j, ND, D*) Boolean value that indicates (for a no-demand point *i* and a demand point *j*) if it exists a no-demand point (in the set *ND*) or a demand point (in the set *D*) closer to *j* and with a higher *HPI* and *GGS* than *i*.

$$E\left(i,j,ND,D\right)=\exists q\in\left(ND\cup D\right)\left|L\left(q,j\right)<L\left(i,j\right)\wedge HPI\left(q\right)>HPI\left(i\right)\wedge GGS\left(q\right)>GGS\left(i\right)\right.$$

SEL(*i, ND, D*) Boolean value that indicates if it exists at least one demand point *j* in the set *D* for which *E*(*i,j,ND,D*) is false. If *SEL*(*i, ND, D*) is true, point *i* is selected as a possible no-demand generation point (see sub-Section 3.2).

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[4] The 3 three different versions of calculating *SelectP()* function are discussed in Section 3.3.

$$SEL(i,ND,D) = \exists j \in D \left| \overline{E(i,j,ND,D)} \right.$$

IGC(*s*, *ND*) Returns the solution with generation in the best (low cost) point of each microgrid or in a no-demand point of set *ND*. For every microgrid *m* of solution *s*, the point *x* (part of the microgrid *m* or of set *ND*) that, if selected as the root, leads to the minimum microgrid cost is defined as microgrid generation point. In this function, set *ND* is dynamic and then does not include no-demand points that are already the generation point of another microgrid part of solution *s*.

$$IGC(s,ND) = s \left| \forall m \in MS(s) : R(m) = \operatorname*{argmin}_{x \in P(m) \cup ND} \left(C\left(MR\left(m,x\right) \right) \right) \right.$$

3.2 Initial filter for pre-selection of possible generation points far from consumption

The initial set of possible generation points far from consumption points could be potentially every point of a certain area but is generally presented in form of a resource grid (i.e. the typical output of a micro-scale wind resource assessment model [4]) with a certain grid spacing (e.g. 100 m). In an area of few square kilometres this set could therefore contain more than 1000 points. In order to screen those that are not interesting a filter is hereby proposed based on the Hybrid Potential Indicator (*HPI*) and the Grid Generation Score (*GGS*) [27].

Being *D* the set of demand points and *IND* the set of initial no-demand points (grid with all possible generation points), the formal definition of set *ND* of pre-selected possible generation no-demand points is hereby reported

$$ND = \left\{ i \in IND \middle| SEL(i,IND,D) \right\}$$

Therefore, the number of pre-selected points depends on the number of users of the community and the number of initial no-demand points. In the studied instances described in Section 4.1 (Table 1 and Table 2) with communities of 10 to 90 users and number of initial no-demands point from 400 to 1600, the filter reduce from 2 up to 15 times the number of possible generation points. The application of the filter in the community of El Alumbre (Peru) is shown in Figure 4. Circle areas are proportional to their *HPI* value. In this case 290 points are pre-selected from an initial pool of 1296 no-demand points. It could be noted that, for instance, points with a low *HPI* located in the north-east and south-east of the community (in areas where demand points are not present) are discarded by the initial filter.

The efficacy of the filter in pre-selecting most promising generation points and its influence on heuristic performance are tested in Section 4.

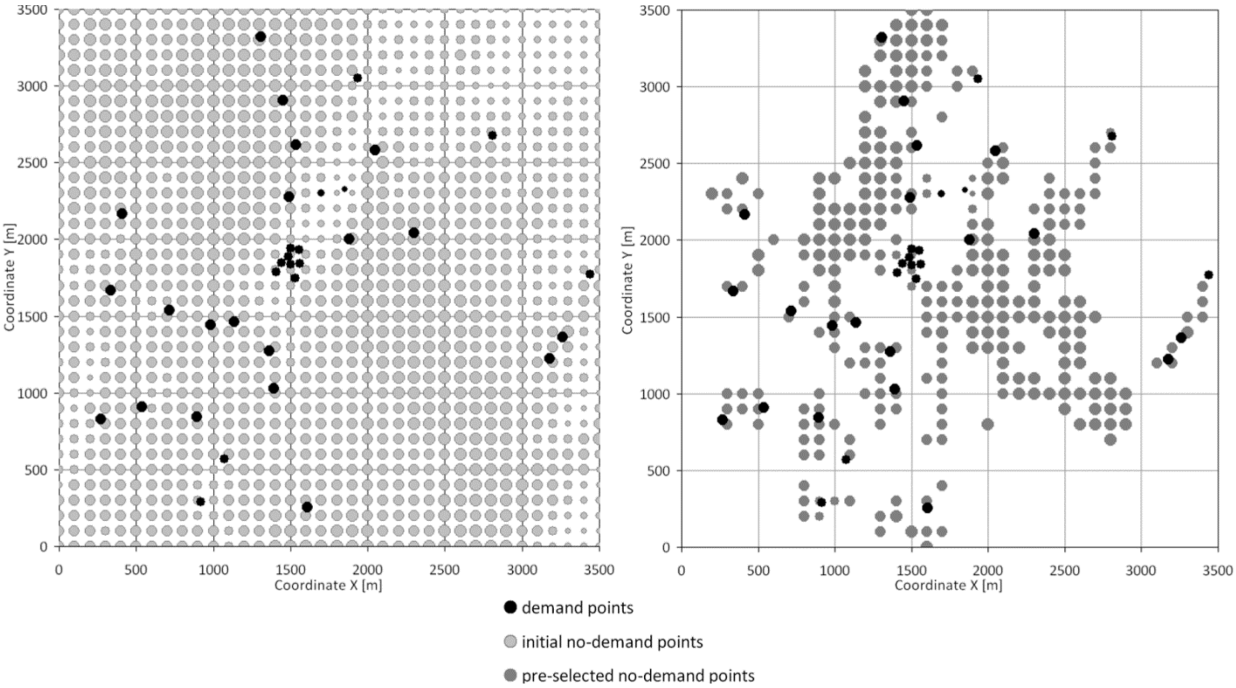

Figure 4 – Pre-selection of possible generation no-demand points in the community of El Alumbre

3.3 Construction phase

The construction phase is based on a greedy algorithm composed by different iterations: in each iteration a microgrid (composed by one or more users) is extended. The initial generation point of each microgrid is selected according to the Grid Generation Score of the point. Demands points are then tried to be connected to the microgrid depending on certain criterion (see function *SelectP*()). The connection is accepted if it leads to a cost decrease (or if microgrid size is equal or smaller than a predefined value P_MIN) and then another point is tried to be connected. It is known that, due to the economy of scale (especially of wind energy), connections between users generally become economically beneficial only when the microgrid in expansion already connects a certain number of users. For this reason, a minimum number of users (parameter P_MIN ≥ 1) are temporally tried to be connected to each microgrid, even if cost increases. The extension of the microgrid ends when the connection is rejected and then the extension of a new microgrid begins. The algorithm ends when all the demand points of the community are part of an extended microgrid or were selected as generation points.

As defined in Section 3.1, there are some functions that are not defined univocally and deserve special attention:

1) Static or dynamic indicators (functions *GGS*(), *NGS*() and *IGS*()): The *GGS*, *NGS* and *IGS* values depends on the number of demand points considered in their calculation. It is not evident a priori if it is better to use static indicators (fixed values of the indicators calculated at beginning considering all the demand points) or dynamic indicators (the indicators are re-calculated as microgrids are actualized considering only the demand points that are not yet connected to any microgrid). Thus these 2 different versions are analyzed and compared in Section 4.2.
2) Selection of point to be connected to the microgrid in expansion (function *SelectP*()): We propose 3 different ways to select the point: only by distance, by a function that depends on the *NGS*, the *IGS* and the distance or by cost difference

(i.e. savings). A priori is difficult to know which way gives best results. Thus, these 3 different versions are analyzed and compared in Section 4.2.

A detailed description of the construction phase is reported in the following.

Initial data

D	Set of demand points
ND	Set of pre-selected no-demand points
P_MIN	Minimum number of demand points that are tried to be connected to a microgrid

Variables

GD	Set of remaining demand possible generation points
GND	Set of remaining no-demand possible generation points
m	Microgrid in expansion during current iteration
x	Initial generation point of *m*
CP	Set of remaining demand points that can be connected to *m*
y	Selected demand point to be connected to *m*
s	Current solution
sn	New solution obtained
AcceptCon	Boolean variable value that indicates if the connection of point *y* to microgrid *m* is accepted or not
Continue	Boolean variable value that indicates if a new connection will be tried or not
*s**	Least cost encountered solution

Algorithm

```
0.  Initialize variables
    0.1 $s^*$ = Solution composed by all independent generation points
    0.2 $GD = D$; $GND = ND$;
1.  While ($GD \neq \emptyset$)
2.      Select a new generation point: $x = \arg\max_{x' \in GD \cup GND} GGS(x')$
3.      Actualize variables:
          3.1 If $x \in D$ then $GD = GD \setminus \{x\}$, $CP = D \setminus \{x\}$ else $GND = GND \setminus \{x\}$, $CP = D$
          3.2 $m = \{x\}$; $s = s^*$; $Continue = \exists y \in CP \mid L(y,m) \leq BED(MP(s,y))$
4.      While ($Continue$ and $CP \neq \emptyset$)
5.          Select the point to be connected to m: $y = SelectP(m, CP, s)$
6.          Actualize variables:
              6.1 $sn = s \setminus \{MP(s,y), m\} \cup MU(m, MP(s,y), \text{false})$
              6.2 $m = MU(m, MP(s,y), \text{false})$; $CP = CP \setminus P(m)$
7.          Connection acceptance criterion: $AcceptCon = (C(sn) < C(s))$ or $|P(m)| \leq$ P_MIN
8.          If $AcceptCon$ then $s = sn$; EndIf
9.          If (($C(s) < C(s^*)$) then $s^* = s$; $GD = GD \setminus P(m)$; EndIf
10.         $Continue = AcceptCon$ and $\exists y \in CP \mid L(y,m) \leq BED(MP(s,y))$
11.     EndWhile
12. EndWhile
```

```
13. Improve generation cost: $s^* = IGC(s^*, ø)$
14. return $s^*$
```

3.4 Local optimization phase

The local optimization phase is composed by two different processes:

1) Microgrids subdivision;
2) Microgrids interconnection.

The two processes are iteratively repeated while solution improves (i.e. the cost is reduced). In the 450 studied instances described in Section 4.1, the application of the “local optimization phase” results to be highly beneficial since it improves the solution obtained by the “construction phase” in around 50% of the instances (mean improvement around 1%) with an increased calculation time of less than 10%.

3.4.1 Microgrids subdivision

During this phase all the microgrids of the solution are tried to be sub-divided into various microgrids. For each microgrid the following steps are carried out:

- The algorithm calculates the cost of dividing the microgrid into 2 smaller microgrids, eliminating one arch of the microgrid. All the arches of the microgrid (sorted in a decreasing order as a function of their cost) are tried to be eliminated.
- If the cost of the 2 new microgrids is lower than the cost of the initial microgrid then the sub-division is accepted. Therefore the same subdivision process is carried out for the 2 resulting microgrids.
- The algorithm stops when no more subdivision is accepted.

A detailed description of the procedure is reported in the following.

Initial data

is	Initial solution
IIM	Set of microgrids part of the initial solution *is* composed by a single demand point.
IMM	Set of microgrids part of the initial solution *is* composed by multiple demand points.
ND	Set of pre-selected no-demand points

Variables

DM	Set of microgrids to be divided
m	Actual microgrid that is tried to be divided
*M**	Set of least cost microgrids
*s**	Least cost encountered solution

Algorithm

```
0. Initialize variables: $M^* = IIM$
1. For ($i \in IMM$)
2.    $DM = \{i\};$
3.    While ($DM \neq ø$)
4.       $m =$ first element of $DM$; $DM = DM \setminus \{m\}$
```

```
5.          If $(Split(m)=\{m\})$ then
6.              $M^* = M^* \cup \{m\}$
7.          Else
8.              $DM = DM \cup Split(m)$
9.          EndIf
10.     EndWhile
11. EndFor
12. Improve generation cost: $s^* = IGC(S(M^*), ND)$
13. return $s^*$
```

3.4.2 Microgrids interconnection

During this phase all the microgrids of the current solution are tried to be interconnected. For each microgrid *m* the following steps are carried out:

- The microgrids located at distance to the microgrid (*m*) lower than their Break-Even Distance (see sub-Section 3.1) are tried to be connected (separately) to *m*. The microgrid *mc* that leads to the highest savings is selected.
- If the connection between microgrids *m* and *mc* decreases the cost of the solution then the two microgrids are connected and the algorithm tries to connect another microgrid to the latter obtained microgrid.
- This process stops when the connection is rejected.

A detailed description of the procedure is reported in the following.

Initial data

is	Initial solution
IM	Set of microgrids part of the initial solution *is* sorted by the number of connected points in descending order (in case of tie, by total cable length in descending order).

Variables

RM	Set of remaining microgrids that should be tried to be interconnected with the other microgrids
m	Actual microgrid that is tried to be interconnected to the other microgrids
CM	Set of remaining microgrids that could be connected to *m*
mc	Selected microgrid to be connected to *m*
s	Current solution
sn	New solution obtained
AcceptCon	Boolean variable that indicates if the connection of microgrids *m* and *mc* is accepted or not
Continue	Boolean variable value that indicates if a new connection will be tried or not
*s**	Least cost solution

Algorithm

```
0. Initialize variables: $RM = IM; s^* = is;$
1. While $(RM \neq \emptyset)$
2.     $m$ = first element of $RM$; $RM = RM \setminus \{m\}$; $CM = MS(s^*) \setminus \{m\};$
```

```
    $s = s^{*}$; $Continue = \exists mc \in CM \,\middle|\, L(mc,m) \le \max\left(BED(mc), BED(m)\right)$
    While ($Continue$ and $CM \neq \varnothing$)
        Select the microgrid to be connected to $m$: $mc = SelectM(m, CM)$
        $m = MU(m, mc, \text{true})$; $CM = CM \setminus \{mc\}$; $sn = S(CM \cup \{m\})$
        Connection acceptance criterion: $AcceptCon = (C(sn) < C(s))$
        If ($AcceptCon$) then $s = sn$; $s^{*} = sn$; $RM = RM \setminus \{mc\}$; EndIf
        $Continue = AcceptCon$ and $\exists mc \in CM \,\middle|\, L(mc,m) \le \max\left(BED(mc), BED(m)\right)$
    EndWhile
EndWhile
Improve generation cost: $s^{*} = IGC(s^{*}, \varnothing)$
return $s^{*}$
```

4. Computational experiment

In the previous Section a heuristic method was presented to design off-grid hybrid wind-photovoltaic (PV) rural electrification systems considering a combination of independent generation points and microgrids and allowing generation also far from demand points.

Hereby, we carried out a computational experiment in order to analyze the results of the proposed heuristic. The utilized instances are described in sub-Section 4.1, then the performance of different algorithm versions are evaluated (sub-Section 4.2) and finally results of the proposed heuristic are compared with existing procedures' solutions (sub-Section 4.3).

4.1 Analyzed instances

The instances were randomly generated based on the characteristics of the 5 real rural electrification projects: El Alumbre and Alto Perú (Peru), Achada Leite (Cape Verde), El Roblar and Sonzapote (Nicaragua). Real projects wind and solar resource data are utilized in order to generate the instances. In each community the wind resource map of the area (with a grid spacing of 100 m) was obtained using a micro-scale wind flow model [4]. The solar resource was estimated by NASA database [38] and it is considered uniform within the areas of the projects, as it is generally done at this scale [29]. The different characteristics of the 5 real projects are resumed in Table 1.

Table 1 – Characteristics of the 5 real projects analyzed

	El Alumbre	Alto Perú	Achada Leite	El Roblar	Sonzapote
Reference name	C1	C2	C3	C4	C5
Area	3.5 x 3.5 km^2	1.5 x 3.5 km^2	2 x 2 km^2	3 x 3 km^2	4 x 4 km^2
Solar Resource: Peak Sun Hours	4.3	4.3	4.8	4.2	4.3
Wind resource: total number of points of the grid resource map	1296	576	400	900	1600
Wind resource: mean wind speed (min and max values of the resource map)	2 – 6.5 m/s	1.5 – 4 m/s	1.1 – 7.5 m/s	1 – 10.2 m/s	0.9 – 9.7 m/s

The electricity requirements of each user (household) are 420Wh/day and 300W of energy and power demand respectively. Regarding electrical equipments, the following data were considered:

- Wind turbines (4 types): nominal power: 100 W, 500 W, 1000 W and 2000 W; cost (including controllers): \$1394, \$4177, \$5906 and \$8732.
- PV panels (3 types): nominal power: 50 W, 75 W and 100 W, cost: \$451, \$636 and \$821.
- PV controller (3 types): maximum power: 50 W, 75 W and 100 W, cost: \$67, \$81 and \$95.
- Batteries (4 types): capacity: 1500 Wh, 1800 Wh, 2400 Wh and 3000 Wh; cost: \$225, \$246, \$292.1 and \$325; efficiency 85%; maximum discharge rate: 0.6; autonomy: 2 days.
- Inverters (4 types): maximum power: 300 W, 1200 W, 1800 W and 3000 W; cost: \$377, \$1200, \$1800 and \$2300; efficiency 85%.
- Electric cables (2 types): costs \$4.9/m and \$5.1/m; resistance: 2.71 and 2.15 Ω/km; maximum intensity: 89 and 101 A; nominal voltage: 220 V; maximum voltage drop: 5%.
- User consumption meter: cost: \$50. Meters are installed only in microgrids composed by multiple users.

The instances have a variable number of users (ranging from 10 to 90 households) and, regarding household distributions, they were randomly generated considering two different concentrations, as in ref. [18], see Table 2. For each type of project, nº of users and type of users' concentration, 5 instances were generated; therefore a total of 450 instances are available.

Table 2 – Characteristics of the generated instances

Type of real project	C1, C2, C3, C4, C5
Nº of users	10, 20, 30, 40, 50, 60, 70 80, 90
Concentration of users	Low (25% of the users in 20% of the area) and High (50% of the users in 20% of the area)

4.2 Selection of best algorithm versions

As defined in the algorithm description, there are different versions of the proposed algorithm that should be studied: the indicators *GGS*, *NGS* and *IGS* could be dynamic or static and there are 3 ways of selection the point to be connected to the microgrid in expansion. Furthermore, it will be evaluated the performance of using or not the initial filter (sub-section 3.2) in each of these algorithm versions. Therefore, the total number of studied algorithm versions is 12 as shown in Table 3.

Table 3 – Different versions of the algorithm

		Selection of point to be connected		
Initial Filter	*Type of indicators*	By distance	By *NGS*, *IGS* and distance	By savings
With Filter	Dynamic indicators	H1	H2	H3
	Static indicators	H4	H5	H6
Without Filter	Dynamic indicators	H7	H8	H9
	Static indicators	H10	H11	H12

In this section all algorithm versions are firstly calibrated (Section 4.2.1) and then performances are compared in order to select the best ones (Section 4.2.2).

4.2.1 Calibration of the algorithm

The algorithm uses a parameter P_MIN that indicates the minimum number of points that are tried to be connected to each microgrid during the “construction phase” (described in Section 3.3). As previously stated, due to the economy of scale (especially of wind energy) a minimum P_MIN value should be imposed in order to ensure microgrids’ feasibility. On the other side, some preliminary calculations showed that the performance of the algorithm with different P_MIN values varies depending on the size of the community, and generally higher P_MIN values are more appropriate for bigger communities. Therefore the parameter P_MIN is defined as the maximum value between a minimum absolute value n and a relative value depending on P, the number of users of a certain community:
P_MIN = Max (n, $\alpha \cdot P$)

Parameters n (ranging from 0 to 5) and α (ranging from 0 to 1 with an interval of 0.1) were calibrated for the 12 algorithm versions on a training set of 90 instances, generated considering the different characteristics reported in Table 2. The values that lead to the best (minimum cost) solutions are:

- P_MIN = Max (4, $0.2 \cdot P$) for H1, H2, H3, H4, H5, H6, H7, H9, H10, H11 and H12;
- P_MIN = Max (4, $0.4 \cdot P$) for H8.

4.2.2 Comparison of the different algorithm versions

The 12 algorithm versions (Table 3) were tested on the 450 instances previously described and obtained results are compared in Table 4. For each algorithm version, the mean computational time and the mean solution cost are shown in columns 2 and 3 of Table 4. In each instance the best solution obtained by the 12 algorithm versions is registered and then the percentage of instances in which a certain version finds a solution that is maximum 1% worst than the best solution is also evaluated (column 4 of Table 4).

Table 4 – Comparison of the solutions obtained by the 12 studied algorithm versions

Algorithm version	Mean computational time [s]	Mean solution cost [$]	Best solution (within 1%)
H1	20.0	88428	63.3%
H2	20.6	88377	64.7%
H3	23.7	88393	64.9%
H4	17.9	88041	77.1%
H5	18.6	88034	78.2%
H6	32.0	88033	78.0%
H7	94.6	88147	71.3%
H8	92.1	88183	74.2%
H9	96.5	88145	73.3%
H10	27.9	88088	74.7%
H11	31.2	88048	78.7%
H12	64.0	88016	78.0%

Regarding the type of indicators, algorithm versions that use static indicators (H4, H5, H6, H10, H11 and H12) are better than versions that use dynamic indicators (H1, H2, H3, H7, H8 and H9): mean solution cost is lower ($88016-88088 counter $88145-88428) and they obtain the best solution in more instances (74.7 – 78.7% counter 63.3 – 74.2%). Furthermore, the computational time of algorithm versions with static indicators is generally lower than that of respective versions with dynamic indicators. Therefore, algorithm versions H1, H2, H3, H7, H8 and H9 are discarded.

Focusing on algorithm versions H4, H5, H6, H10, H11 and H12, it should be noted that their results are really similar (low variance) with mean solution costs between $88016 and $88088 and finding the best solution in almost 80% of the instances. The utilization of the initial filter for pre-selection of possible generation points does not affect the quality of the solution obtained, as couples H4 - H10, H5 - H11, H6 - H12 generally find similar solutions. However, as expected, algorithm versions that utilize the initial filter (H4, H5 and H6) are faster than the respective versions that do no apply the filter. This confirms the efficacy of the filter in pre-selecting most promising generation points and reducing the computational time. On the other side, solutions obtained are affected by the way in which the connected point is selected: many times H4, H5 and H6 (and respectively H10, H11 and H12) obtain different solutions. It should be noted that algorithm versions that calculate the savings (H6 and H12) require a longer time in comparison with the others, without strictly obtaining a better solution.

As their computational times are low, it is hereby proposed to compare the following 2 ensembles (an ensemble hereby refers to the launch of a certain set of algorithm versions and the best solution found by the set is considered):

1) ESF (Ensemble with Static indicators and Filter): composed by H4, H5 and H6
2) ESNF (Ensemble with Static indicators and No-Filter): composed by H10, H11 and H12.

It should be noted that the use of ensemble of algorithm versions reduces the total computational time, as some computations do not need to be repeated, such as the indicators calculation and the application of the initial filter.

The ensemble ESF performs better than ensemble ESNF (Table 5): ESF mean solution cost is lower ($87615 counter $87625) and it obtains the best solution in more instances (93.6% counter 92.2%) with a lower computational time (43.3 s counter 106.1 s).

Table 5 –Comparison between ensembles ESF and ESNF

Type of ensemble	Mean computational time [s]	Mean solution cost [$]	Best solution (within 1%)
ESF	43.3	87615	93.6%
ESNF	106.1	87625	92.2%

Therefore, the ensemble ESF that apply the initial filter and use static indicators is selected as the proposed heuristic of this study.

4.3 Comparison with existing procedures

Hereby, the solutions of the proposed heuristic ("ESF") are compared with the ones obtained by existing heuristic and exact procedures for solving the AVEREMS problem. All calculations were done on a PC Intel Core 2 i7-2600 3.4 GHz with 8 GB of RAM.

4.3.1 Comparison with heuristic procedures

As introduced there are two heuristic procedures currently available for the design of off-grid community electrification projects considering resource variations and microgrid distributions: VIPOR [19] (a commonly utilized software for stand-alone microgrids design [26, 31, 39]) and the heuristic proposed by ref. [27] (this procedure considers the design of a single microgrid and from now on is called "SMH", Single Microgrid Heuristic).

VIPOR have some limitations that differ from ESF and SMH. In order to obtain comparable results the following hypotheses were assumed:

- VIPOR considers a continuous generation – cost curve, i.e. installation cost as a function of the generated energy, for every possible generation point. In fact it defines the distribution system, i.e. users connections and generation systems position, but do not designs the generation system, i.e. the number of controllers/batteries/inverters to be installed in each generation point (see Fig. 1). This task should be done by a different software [26]. On the other side, ESF and SMH consider a discrete curve and they design both the generation and the distribution systems. In order to solve this issue and make reliable the comparison the following assumptions were done:
    - To obtain the maximum precision in input data, the continuous generation-cost curve for VIPOR was obtained calculating the initial investment cost (including generators, controllers, batteries and inverters) considering a variable energy demand when connecting one by one all the demand points of the community.
    - From each obtained VIPOR solution configuration, the number of generation/storage/control equipments to be installed is calculated according to ref. [18], as it is done by ESF and SMH.

- VIPOR considers a single type of cable for low voltage distribution and no voltage losses are considered, therefore a unique cable with unitary cost \$5/m and null resistance is considered also for ESF and SMH.
- VIPOR limits to 10 the number of possible generation points. Two cases will be analyzed: pre-select the 10 points with higher wind resource (called “V1”) or pre-select the 10 points with higher *GGS* (called “V2”).

The solutions obtained by SMH, ESF and VIPOR (versions V1 and V2) in a selection of 50 instances representatives of all project types, nº of users and types of users concentrations are shown in Table 6. In each of the analyzed instances, the computational time of the 3 heuristics is less than 180 s. In the comparison between VIPOR (V1 and V2) and ESF solution (last 4 columns of Table 6) the following data are presented: the mean difference between both solutions (“Difference” columns) and the number of instances in which ESF improves VIPOR solution of more than 5% (“Improv. > 5%” columns).

Solutions obtained by the SMH are always equal or worst than solutions obtained by both VIPOR and ESF; mean improvements of the ESF in comparison with SMH is around 13.6%.

Regarding VIPOR solutions, version V2 (pre-selecting generation points by higher *GGS*) performs on average better that version V1 (that pre-selects generation points just by wind potential) in all project types’ a part from C2, where the lowest wind resource is present. This confirms the utility of the indicator *GGS* in pre-selecting most promising grid generation points, especially in sites with good wind resource.

In no instances both VIPOR versions’ solution is more than 1% better than ESF solution. On the other side, the ESF improves VIPOR solutions of more than 5% in around 50% of the instances with mean improvements around 6.6% and 5.6% in comparison with V1 and V2 respectively.

Table 6 – Comparison between SMH, VIPOR and ESF solution costs (in US\$)

		SMH	ESF		VIPOR		Comparison VIPOR – ESF			
					V1	V2	Comp. with V1		Comp. with V2	
		Sol. cost	Sol. cost	Improv. to SMH	Sol. cost	Sol. cost	Difference	Improv. > 5 %	Difference	Improv. > 5 %
Project type	C1	103415	88951	11.2%	95546	94644	6.4%	60%	5.0%	50%
	C2	105155	95360	7.1%	98355	100590	2.2%	10%	4.0%	40%
	C3	103382	77991	19.2%	87725	84377	7.6%	50%	5.9%	50%
	C4	103562	82984	16.0%	92918	90136	9.3%	70%	6.3%	50%
	C5	103128	85800	14.6%	93652	92544	7.2%	70%	6.6%	70%
Nº users	10	20835	19798	5.0%	20418	20274	3.0%	20%	2.4%	20%
	30	61355	55896	8.9%	58751	57939	4.8%	40%	3.5%	20%
	50	103886	87753	15.5%	93887	94189	6.5%	60%	6.8%	70%
	70	145431	119675	17.7%	130099	127309	8.1%	60%	5.9%	60%
	90	187135	147964	20.9%	165041	162580	10.4%	80%	9.1%	90%
Users concentration	Low	103766	87818	12.3%	94257	93169	5.2%	36%	4.7%	44%
	High	103691	84616	15.0%	93022	91747	8.0%	68%	6.4%	60%
Total		103728	86217	13.6%	93639	92458	6.6%	52%	5.6%	52%

The improvement of the ESF in comparison with VIPOR depends on the wind resource of the project, the nº of users of the instance and the type of users' concentration:

- As higher the wind resource higher the improvement: the lowest improvements (2.2% in comparison with V1) are obtained in instances C2 where the lowest wind resource is present, while highest improvements are obtained in C4 (9.4% in comparison with V1) which is the project with the highest wind resource.
- As the size of the instance increases also the differences between VIPOR and ESF increase. In instances bigger than 30 users ESF enhances VIPOR of more than 5% in more than 50% of the instances.
- Higher improvements are obtained in instances with higher users' concentration: mean enhancements of 5.2% and 8.0% (in comparison with V1) are obtained respectively for the low and high users' concentration instances.

It can be concluded that the proposed heuristic considerably enhances solutions obtained by VIPOR software, a commonly utilized tool for designing stand-alone microgrids (e.g ref. [26] and ref. [39]). Moreover, as previously stated, the proposed heuristic is a complete design tool that defines both the generation and the distribution systems (see fig. 1), while VIPOR just focuses on the distribution system with some limitations (such as the reduced number of grid generation points, the single cable type and the no consideration of voltage drops).

4.3.2 Comparison with exact procedure

Solutions of the ESF are hereby compared with solutions obtained by the mixed integer linear programming (MILP) model described in ref. [18]. The MILP model was solved using the IBM ILOG CPLEX 12.2 Optimizer considering a maximum computation time of 3600 seconds for each instance. As the MILP consider just demand point as possible generation points, the same limitative hypothesis was assumed in the calculations with the ESF. Table 7 presents the comparison between solutions obtained by the MILP model and the ESF. MILP model and ESF mean solution costs and computational times are shown in columns 3-4 and 6-7 respectively. With respect to MILP model solution, the difference between the solution cost and the lower bound found by the model (called "Gap") is presented (column 5). In the comparison between MILP and ESF, besides the mean difference between both solutions (column 8), the percentage of instances in which ESF improves MILP solution of more than 5% (column 9) and the percentage of instances in which MILP improves ESF solution of more than 5% (column 10) are presented.

The comparison between MILP and ESF solutions is highly dependent on the size of the instance. For instances of 10 users in which optimal solutions are obtained by MILP model (Gap = 0%), ESF solutions are nearly optimal with a mean cost difference lower than 0.1% with respect to MILP model. For instances up to 40 users (in whose the Gap of the MILP model is lower than 20%) similar solutions are found by both procedures. However, in no instances MILP solution is more than 5% better than ESF solution. As the instance size increases the proposed heuristic finds better solutions in comparison with the MILP with mean improvements of 1.5% in communities of 50 users and up to 16% for communities of 90 users. For instances of more than 60 users, the ESF enhances the MILP of more the 5% in more than 50% of the cases. The overall improvement of the ESF (with a computational time lower than 1 minute in all instances) in comparison with the MILP (with a maximum computational time of 1 hour) is 4.3%.

Table 7 – Comparison between MILP and ESF solution costs (in US$) and computational times (in seconds)

		MILP model			ESF		Comparison MILP – ESF		
		Sol. cost	Comput. time	Gap	Sol. cost	Comput. time	Diff.	Improv. ESF >5%	Improv. MILP >5%
Project Type	C1	94956	3203	20.5%	89981	3.9	3,2%	22,2%	0,0%
	C2	104212	3276	16.1%	99138	18.3	3,0%	27,8%	0,0%
	C3	98468	3213	27.4%	83651	7.4	8,0%	41,1%	0,0%
	C4	94287	3164	21.5%	86633	7.8	5,0%	33,3%	0,0%
	C5	88676	2992	16.2%	85505	5.1	2,3%	14,4%	0,0%
Nº users	10	19929	172	0.0%	19944	0.4	-0,1%	0,0%	0,0%
	20	38379	3215	4.2%	38338	0.9	0,1%	0,0%	0,0%
	30	56634	3541	11.4%	56610	1.6	0,0%	0,0%	0,0%
	40	73881	3600	17.0%	73377	3.2	0,6%	2,0%	0,0%
	50	91171	3600	21.0%	89750	5.3	1,5%	8,0%	0,0%
	60	110000	3601	25.1%	106384	8.2	3,1%	14,0%	0,0%
	70	130944	3600	30.0%	122422	14.3	6,3%	52,0%	0,0%
	80	157381	3600	34.9%	139539	18.2	11,0%	82,0%	0,0%
	90	186756	3600	39.4%	154471	24.3	16,0%	92,0%	0,0%
Users concentration	Low	96633	3158	19.4%	89980	8.2	4,1%	28,0%	0,0%
	High	95607	3181	21.2%	87983	8.8	4,5%	27,6%	0,0%
Total		96120	3170	20.4%	88982	8.5	4.3%	27.8%	0.0%

Finally it should be noted that considering the ESF computational time as the maximum MILP model computational time, no solution can be found by the MILP model in all analyzed instances. Moreover, as previously stated, MILP model limits generation location close to the users while the proposed heuristic does not have this limitation and permits generation far from demand points.

5. Conclusions

This study presents a heuristic procedure to design rural community off-grid electrification projects based on wind and solar energies considering micro-scale resource variations, generation close or far from demand points and a combination of independent generation points and microgrids. The heuristic is based on a greedy algorithm that makes use of some indicators recently proposed by literature.

Firstly a filter in order to pre-select most promising generation points located far from demand points is presented. Then different algorithm versions were tested and the ensemble of the best solution of 3 different versions was selected.

Finally proposed heuristic solutions were compared with existing heuristics and exact procedures. The proposed heuristic can enhance solutions obtained by currently utilized VIPOR software of more than 5% in around 50% of the instances with mean improvements of around 6%. The proposed heuristic compares well also with existing exact procedure (MILP model): similar solutions where found for instances of up to 40 users, while for bigger instances the proposed heuristic (with a computational time lower than 1 minute) considerably enhances solutions obtained by the MILP model (with a computational time of 1 hour).

The proposed heuristics is a complete and simple design tool that can efficiently support the design of stand-alone community electrification projects requiring of low computational resources. Future studies will be carried out in order to further improve the performance of the procedure.

Acknowledgements

This paper was supported by the Spanish Ministry of Education (FPU grant AP2009-0738), the MICINN project ENE2010-15509 and co-financed by the Centre for Development Cooperation of the Universitat Politècnica de Catalunya. The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper.

Appendix A – A MILP model to solve the AVEREMS problem

The mathematical formulation of the MILP model presented in ref. [18] considering wind and solar energies is hereby reported.

Data

Consumption points:

P	Number of consumption points (which may be, for instance, households, schools, health centers or community centers). These are the points where the generators can be placed.
L_{pd}	Distance [m] between two points p and d (p= 1,…, P; d = 1,…, P).
L_{max}	Maximum length of segment of a wire of the microgrid.
Q_p	Set of points d to which a point p could be directly joined with a wire segment (p= 1,…, P; d = 1,…, P: $p \neq d$, $L_{pd} \leq L_{max}$).
ED_p	Electric energy demand [Wh/day] at p (p = 1,…, P).
PD_p	Power demand [W] at p (p = 1,…, P).
CM	Cost [US$] of an electric meter.

Wind Generation:

A, NA	Types of wind turbines (a = 1,…, A) and maximum number of wind turbines that can be placed at a point, respectively.
EA_{pa},	Energy generated [Wh/day] by a wind turbine placed at point p of the type a (p = 1,…, P; a = 1,…, A).
PA_a	Maximum power [W] of a wind turbine of type a (a = 1,…, A).
CA_a	Cost [US$] of a wind turbine of type a (a = 1,…, A).
R	Types of battery charge wind controllers (r = 1,..., R).
PR_r	Maximum power [W] of a battery charge wind controller of type r (r = 1,…, R).
CR_r	Cost [US$] of a battery charge wind controller of type r (r = 1,…, R).

PV Generation:

S, NS	Types of PV panels (s = 1,…, S) and maximum number of PV panels that can be placed at a point, respectively.
ES_s,	Energy generated [Wh/day] by a PV panel of the type s (s = 1,…, S).
PS_s	Maximum power [W] of a PV panel of type s (s = 1,…, S).
CS_s	Cost [US$] of a PV panel of type s (s = 1,…, S).
Z	Types of PV battery charge controllers (z = 1,…, Z).
PZ_z	Maximum power [W] of a battery charge PV controller of type z (z = 1,…, Z).
CZ_z	Cost [US$] of a battery charge PV controller of type z (z = 1,…, Z).

Energy storage:

B	Types of batteries (b = 1,…, B).
ηb	Efficiency of the batteries [fraction of unity].
DB	Maximum proportion of discharge admitted in the batteries.
VB	Required autonomy of the batteries [days].
EB_b	Capacity [Wh] of a battery of type b (b = 1,…, B).
CB_b	Cost [US$] of a battery of type b (b = 1,…, B).
I	Types of inverters (i = $1,..., I$).
ηi	Efficiency of the inverters [fraction of unity].
PI_i	Maximum power [W] of an inverter of type I (i = 1,…, I).
CI_i	Cost [US$] of an inverter of type I (i = 1,…, I).

Microgrid:

C	Types of microgrid wires.

RC_c Electric resistance (feed and return) [Ω/m] of a wire of type c ($c = 1,\ldots, C$).

IC_c Maximum intensity [A] of a wire of type c ($c = 1,\ldots, C$).

CC_c Cost [US$/m] of a wire of type c (feed and return), including the cost of infrastructure ($c = 1,\ldots, C$).

V_N , $V_{min,}$,V_{max} Nominal, Minimum and Maximum voltage [v], respectively.

ηc Efficiency of the microgrid [fraction of unity].

Variables

The model uses the following types of variables:

- Integer non-negative variables to define the location and sizing of equipment

xa_{pa} Number of wind turbines of type a is placed at point p ($p = 1,\ldots,P;\ a = 1,\ldots,A$).

xs_{ps} Number of PV panels of type s is placed at point p ($p = 1,\ldots,P; s = 1,\ldots,S$).

xb_{pb} Number of batteries of the type b is placed at point p ($p = 1,\ldots,P; b = 1,\ldots,B$).

xr_{pr} Number of battery charge wind controllers of type r is placed at point p ($p = 1,\ldots,P; r = 1,\ldots,R$).

xi_{pi} Number of inverters of the type i is placed at point p ($p = 1,\ldots,P; i = 1,\ldots,I$).

xz_{pz} Number of battery charge PV controllers of type z is placed at point p ($p = 1,\ldots,P; z = 1,\ldots,Z$).

- Float non-negative variables to define energy and power flows and voltage

fe_{pd} Flow of energy [Wh/day] between the points p and d ($p = 1,\ldots,P; d \in Q_p$).

fp_{pd} Flow of power [W] between the points p and d ($p = 1,\ldots,P; d \in Q_p$).

v_p Voltage [V] at the point p ($v_p = V_{min},\ldots,V_{max}; p = 1,\ldots,P$).

- Binary variables to define the generation points, the microgrid and the meters.

$xg_p \in \{0;1\}$ 1, if some wind turbine and/or PV panel is placed at point p ($p = 1,\ldots,P$).

$xc_{pdc} \in \{0,1\}$ 1, if there is a wire of type c between the points p and d ($p = 1,\ldots,P; d \in Q_p; c = 1,\ldots,C$).

$xm_p \in \{0,1\}$ 1, if an electric meter is placed at point p ($p = 1,\ldots,P$).

Objective function

The objective function (1) minimizes the initial investment costs, considering the generation, storage and distribution equipment.

$$\begin{aligned}[MIN]Z = {} & \sum_{p=1}^{P}\sum_{a=1}^{A} CA_a \cdot xa_{pa} + \sum_{p=1}^{P}\sum_{s=1}^{S} CS_s \cdot xs_{ps} + \sum_{p=1}^{P}\sum_{b=1}^{B} CB_b \cdot xb_{pb} + \\ & \sum_{p=1}^{P}\sum_{d\in Q_p}\sum_{c=1}^{C} L_{pd} \cdot CC_c \cdot xc_{pdc} + \sum_{p=1}^{P}\sum_{i=1}^{I} CI_i \cdot xi_{pi} + \\ & \sum_{p=1}^{P}\sum_{r=1}^{R} CR_r \cdot xr_{pr} + \sum_{p=1}^{P}\sum_{z=1}^{Z} CZ_z \cdot xz_{pz} + \sum_{p=1}^{P} CM \cdot xm_p\end{aligned} \tag{1}$$

Constraints

Constraint (2) defines the points at which wind turbines are placed and limits the maximum number of generators at the same point; in an analogous way (3) incorporates PV panels.

Constraint (4) forces xg_p to be equal to 0 if neither a wind turbine nor a PV panel is placed at point p. Energy and power balances and conservation are described in (5) and (6), respectively. Constraint (7) establishes the capacity of the batteries. Constraints (8) and (9) relate the energy and power flows respectively, to the existence of a wire between two points. The radial distribution of the microgrid is established in (10), constraint (11) limits the voltage drops and (12) the maximum intensity. The power of battery charge wind controllers is defined in (13). In a similar way, the power of battery charge solar controllers is defined depending on the power of the corresponding PV panel (14). Inverters can only be placed at points where wind-PV generators are placed (15). Constraints (16) and (17) force the installation of electric meters at the consumption points fed by a microgrid.

$$\sum_{a=1}^{A} xa_{pa} \leq NA \cdot xg_p \qquad p = 1,\ldots,P \tag{2}$$

$$\sum_{s=1}^{S} xs_{ps} \leq NS \cdot xg_p \qquad p = 1,\ldots,P \tag{3}$$

$$\sum_{a=1}^{A} xa_{pa} + \sum_{s=1}^{S} xs_{ps} \geq xg_p \qquad p = 1,\ldots,P \tag{4}$$

$$\begin{aligned}\sum_{q=1|p\in Q_q}^{P} fe_{qp} + \sum_{a=1}^{A} EA_{pa} \cdot xa_{pa} + \sum_{s=1}^{S} ES_s \cdot xs_{ps} \geq \\ \frac{ED_p}{\eta b \cdot \eta i}\left(\frac{1}{\eta c} + \left(1 - \frac{1}{\eta c}\right) xg_p\right) + \sum_{d\in Q_p} fe_{pd} \qquad p = 1,..,P\end{aligned} \tag{5}$$

$$\sum_{q=1|p\in Q_q}^{P} fp_{qp} + \sum_{i=1}^{I} PI_i \cdot xi_{pi} \geq PD_p\left(\frac{1}{\eta c} + \left(1 - \frac{1}{\eta c}\right) xg_p\right) + \sum_{d\in Q_p} fp_{pd} \qquad p = 1,\ldots,P \tag{6}$$

$$\sum_{b=1}^{B} EB_b \cdot xb_{pb} + \left(\frac{VB}{DB}\sum_{j=1}^{P}\frac{ED_j}{\eta b \cdot \eta i \cdot \eta c}\right)\left(1 - xg_p\right) \geq \frac{VB}{DB}\left(\sum_{d\in Q_p} fe_{pd} + ED_p\right) \qquad p = 1,\ldots,P \tag{7}$$

$$fe_{pd} \leq \left(\sum_{j=1}^{P}\frac{ED_j}{\eta b \cdot \eta i \cdot \eta c}\right)\sum_{c=1}^{C} xc_{pdc} \qquad p = 1,\ldots,P; d \in Q_p \tag{8}$$

$$fp_{pd} \leq \left(\sum_{j=1}^{P}\frac{PD_j}{\eta c}\right)\sum_{c=1}^{C} xc_{pdc} \qquad p = 1,\ldots,P; d \in Q_p \tag{9}$$

$$\sum_{q=1|p\in Q_q}^{P}\sum_{c=1}^{C} xc_{qpc} + xg_p \leq 1 \qquad p = 1,\ldots,P \tag{10}$$

$$v_p - v_d \geq \frac{L_{pd} \cdot RC_c \cdot fp_{pd}}{V_n} - \left(V_{max} - V_{min}\right)(1 - xc_{pdc}) \qquad p = 1,\ldots,P; d \in Q_p; c = 1,\ldots,C \tag{11}$$

$$\frac{fp_{pd}}{V_n} - \left(\sum_{j=1}^{P}\frac{PD_j}{V_{min} \cdot \eta c}\right)(1 - xc_{pdc}) \leq IC_c \qquad p = 1,\ldots,P; d \in Q_p; c = 1,\ldots,C \tag{12}$$

$$\sum_{r=1}^{R} PR_r \cdot xr_{pr} \geq \sum_{a=1}^{A} PA_a \cdot xa_{pa} \qquad p = 1,\ldots,P \tag{13}$$

$$\sum_{z=1}^{Z} PZ_z \cdot xz_{pz} \geq \sum_{s=1}^{S} PS_s \cdot xs_{ps} \qquad p = 1,\ldots,P \tag{14}$$

$$xi_{pi} \leq NI \cdot xg_p \qquad p = 1,\ldots,P; i = 1,\ldots,I \tag{15}$$

$$\sum_{d \in Q_p} \sum_{c=1}^{C} xc_{pdc} \leq (P-1)\, xm_p \qquad p = 1,\ldots,P \tag{16}$$

$$\sum_{q=1 | p \in Q_q}^{P} \sum_{c=1}^{C} xc_{qpc} \leq xm_p \qquad p = 1,\ldots,P \tag{17}$$

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Annex A2. Articles submitted to journals included in the JCR index

A GRASP based method to design off-grid community electrification projects with renewable energies

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Abstract

The design of off-grid electrification projects considering hybrid systems and distribution microgrids is a complex task that requires the use of decision support tools. Most of existing tools focus on the design of hybrid systems without defining generator locations and microgrids configuration. Recently a deterministic heuristic was developed to solve the problem. In this study we present an enhanced deterministic heuristic and then a meta-heuristic procedure, based on the GRASP, for designing community off-grid electrification projects based on renewable energies considering micro-scale resource variations and a combination of independent generation points and microgrids. Both new algorithms improve performance of the previous existing procedure. The new deterministic heuristic can rapidly (in a computational time lower than 1 minute) obtain a good solution. On the other hand, the proposed GRASP based method considerably enhances solutions obtained by the deterministic heuristic with a computational time of 1 hour on a standard PC. The improvement tends to raise as the complexity of the analyzed instance increases. The proposed algorithm is a complete design tool that can efficiently support the design of stand-alone community electrification projects requiring of low computational resources.

Nomenclature

- Arch: segment of electric cable that connects 2 points of a microgrid.
- Branch: set of users (and arches) of a microgrid connected to the generation system passing from the same point. All branches of a microgrid include the generation point.
- Community: a group of users.
- Demand point (or user): location of a consumption point, such as a house or a public building, with certain electric energy and power demands. Demand points can be generation points.

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- Distribution system: the electric cables that connect the generation system to the users.
- Generation point: location where a generation system is installed.
- Generation system: group of components installed in a certain point in order to generate and store the electricity. It includes generators (wind turbines and solar panels), controllers, batteries and inverters.
- Grid consumption point (or no-generation point): a user connected to a multiple points' microgrid and not being the generation point. It just consumes energy.
- Grid generation point: generation point of a microgrid composed by multiple points
- Independent generation point (or independent generation system): a user that is producing energy just for its own consumption.
- Microgrid: set of one or more users fed by a generation system placed in a demand or no-demand point. It includes both the generation and the distribution systems.
- No-demand point: location (that is not a demand point) that can be a generation point.
- Solution: set of microgrids.

1. Introduction

Projects relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously [1], [2]. These systems produce electricity in a clean way, their cost is often lower than national grid extension and they are not dependent from continuous fuel supply (such as diesel generators), therefore increasing projects long-term sustainability [2]. In this context, the configurations that proved to be the most reliable design options are hybrid systems that combine different generation resources [3], [4] and distribution microgrids, where the energy is produced in a certain point and distributed through an electric microgrid to other consumption points [5], [6].

The design of off-grid renewable energy projects considering hybrid systems and distribution microgrids must consider multiple issues. When designing hybrid systems, the most adequate combination of technologies should be evaluated depending on available resources and generation and storage equipments characteristics. When designing microgrids, the selection of grid generation points and the definition of which points should be connected to a certain micro-grid and which not, are complex tasks, especially when resource (e.g. the wind) is highly disperse [7] and best areas for installing generators could be located far from demand points [8]. Furthermore, in scattered communities with isolated users, the combination of multiple microgrids and independent generation points is generally the cheaper design solution [9].

Over last decade, many tools have been developed in order to support the design [10]. However, most of them define the best combination of energy resources in one point but without designing the distribution through microgrids and without taking into account resource spatial variations. The only known method that permits the design of off-grid electrification projects based on multiple renewable energies considering micro-scale resource variations, a combination of independent generation points and microgrids and considering generation in every point of an area (not only close to the users) is the deterministic greedy heuristic proposed by ref. [11].

The problem solved is called AVEREMS: the Autonomous Village Electrification through Renewable Energy and Microgrid Systems [11]. The solutions of that algorithm were shown to considerably improve those obtained by other procedures that, with some limitations, deal with the same design problem: VIPOR software [12] and the mathematical model presented in ref. [9]. However, the algorithm proposed by ref. [11] has some possible weaknesses. Firstly, it creates microgrids always minimizing cable length, while in some cases it would be preferable to utilize a different network configuration in order to reduce utilized cable unitary cost and thus microgrid cost. Furthermore, it is a deterministic procedure in which a single solution is greedily constructed and then improved by a local search phase. It should be noted that the solution obtained by the local search, i.e. local optimum, could be far from the global optimum, i.e. the best of all feasible solutions.

In the last few decades, various meta-heuristic procedures have been developed in order to escape from local optima and thus improve solutions encountered by deterministic heuristics [13]. One of those is the GRASP (Greedy Randomized Adaptive Search Procedure) [14] that has been successfully applied to various location optimization problems [15]. In particular, a GRASP based procedure demonstrated to be highly efficient in solving the capacitated plant location problem [16],which has various similarities with the AVEREMS problem (see ref. [11]).

In this study we present an improved deterministic heuristic and then a meta-heuristic procedure, based on the GRASP, for solving the AVEREMS problem; that is, for designing community off-grid electrification projects based on renewable energies considering micro-scale resource variations and a combination of independent generation points and microgrids. The proposed algorithm aims to improve the performance of the currently available procedure.

The rest of the paper is organized as follows. Section 2 presents the components of a general off-grid electrification project and the basic problem statement of the AVEREMS. An enhancement to the deterministic heuristic method described in ref. [11] is proposed in Section 3. Various versions of the proposed GRASP based algorithm are described in detail in Section 4. In Section 5 the best version is identified and its performance is compared with the existing procedure. Section 6 deals with the conclusions.

2. The AVEREMS problem

In this Section the components of a hybrid off-grid electrification system are presented (sub-Section 2.1) and the AVEREMS problem is described (sub-Section 2.2).

2.1 Components of an off-grid electrification system

The scheme of the elements involved in an autonomous electrification system considering wind and solar energies is as follows (Fig. 1):

1) Generators: produce energy in alternating (wind turbines) or direct (solar panels) current.

2) Controllers: convert to direct current (DC) and control the charge/discharge of the batteries.

3) Batteries: store the energy produced by the generators, receive and supply electricity at DC.

4) Inverters: convert direct to alternating current (AC) at the nominal voltage.

5) Electric cables: configure the microgrid that distributes the energy (only low voltage distribution is considered).

6) Electric meters: measure the energy consumed at the demand points.

7) Users (or Demand points): consume the energy.

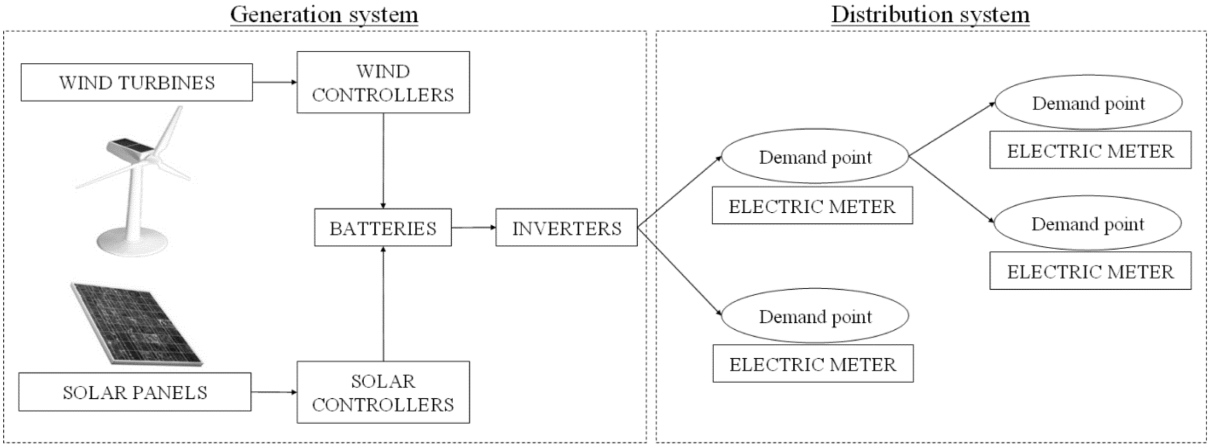

Fig. 1 – Components of an off-grid hybrid wind-photovoltaic electrification system

The generation system in a location (or generation point) is composed by the generators (wind turbines and/or solar panels), controllers, batteries and inverters. The energy produced by a generation system is distributed to the users by electric cables (distribution system). The term “microgrid” in this paper refers to the ensemble of the generation and the distribution systems. A microgrid composed by a single demand point with the generation system located in the same point is also referred to as an “independent generation point”. The radial microgrid configuration (i.e. a single generation system per microgrid and distribution in form of a tree as in Fig. 1) is considered in this study as it is the preferred one in rural electrification projects [12], [17].

2.2 Problem statement

The aim of the AVEREMS design problem is to find the lowest cost configuration (generation points’ locations and microgrids design) that accomplish with the energy and power demands of all the users, taking into account energy resource maps and different technical constraints. A detailed description of the AVEREMS problem constraints and mathematical formulation is reported in ref. [11]. Next, the objective function of the problem and the constraints of the generation and distribution systems (Fig. 1) are resumed:

- Objective function: To minimize the cost of the project, considering all components defined in Fig. 1, i.e. wind turbines, wind controllers, solar photo-voltaic (PV) panels, solar controllers, batteries, inverters, meters, and cables.
- Constraints of the *generation system*: In each generation point, generators, controllers, inverters and batteries must be installed in order to cover the energy and power demands of connected users. Generators and batteries must satisfy the energy demand, while inverters must fulfill the power demand. For the dimensioning of the generators, batteries and inverters the following aspects must be also considered: energy resources available in the area, energy and power losses due to equipments’ efficiencies, the minimum days of autonomy and the maximum battery discharge factor. Controllers are dimensioned depending directly on the installed generators. Generation systems could be located in every point of a certain area (thus not forcedly close to demand points as considered by ref. [9]).
- Constraints of the *distribution system*: Every demand point must be connected to the generation system by an electric cable. The type of cable installed must satisfy maximum permitted voltage drop considering nominal distribution voltage, and cable resistance and

maximum intensity. Microgrid structure is radial. Consumption meters must be installed in microgrids connecting multiple users.

Fig. 2 shows a solution to the AVEREMS problem in a community of 22 users distributed on an area of 1 km x 1 km. For each generation point, besides generators (indicated in Fig. 2), the number and type of the other components to be installed in the generation system, i.e. controllers, batteries and inverters (Fig. 1), must be specified. For each branch of a microgrid the type of cable must be specified in order to fulfill with distribution system constraints.

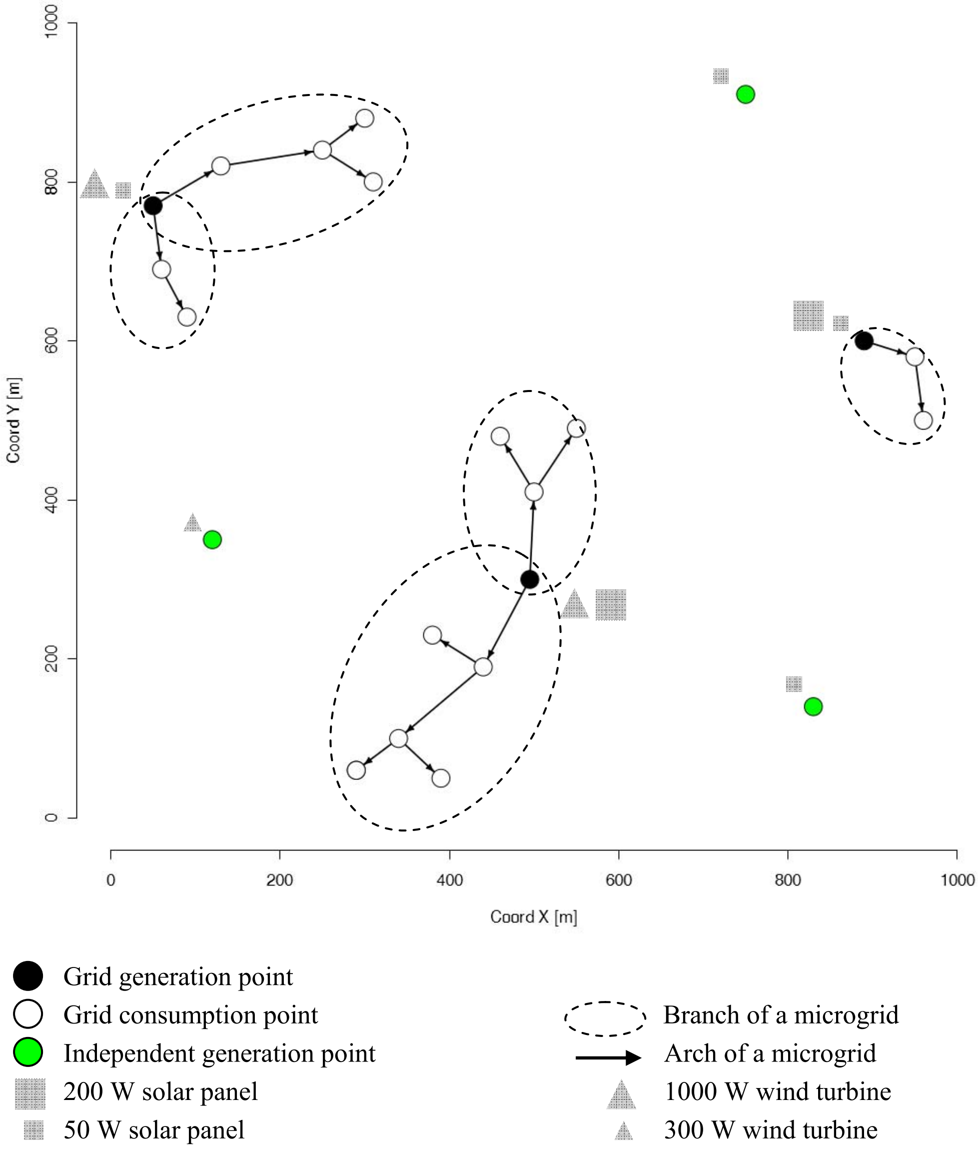

Fig. 2 – Example of a solution to the AVEREMS problem in a community composed by 22 users

3. Enhanced deterministic heuristic

The heuristic algorithm presented in ref. [11] is a fast method to solve the AVEREMS problem. This algorithm is composed by 2 phases: first construction, and then a local optimization. In the "construction phase", the solution considering all independent generation points is firstly calculated, and then the algorithm iteratively extends microgrids as much as possible, according to the cost criterion. The “local optimization phase” is composed by 2 steps that are repeated if they improve the previously obtained solution: firstly the microgrids are divided (if this reduces solution cost) into smaller ones and then the resulting microgrids are tried to be interconnected between them.

That heuristic creates microgrids always following the minimum spanning tree procedure [18], which, given a generation point and a set of users to connect, returns the configuration network that minimizes cables length. However, the distribution system cost depends on both the cable length and the cable type (i.e. unitary cost) used in order to fulfil distribution system constraints, such as maximum permitted voltage drop. Therefore, in some cases it could be better, in order to reduce the distribution cost, to utilize a network configuration with a longer cable length (not the minimal) but that permits the installation of a less expensive cable type.

In order to take into account this issue, we propose an enhanced deterministic algorithm based on the one described in ref. [11] including an additional third phase that aims to reduce distribution system cost (Fig. 3). The performance comparison between this algorithm and the previous one is analyzed in the carried out computational experiment (sub-Section 5.2). In this Section the algorithm is presented. First, the internal functions used are defined (sub-Section 3.1). Then the main features of the “construction phase” (adapted from ref. [11]) are described (sub-Section 3.2); the “local optimization phase” does not change with respect to the previous one [11] and thus is not described here. Finally the “distribution system optimization phase” is presented in detail (sub-Section 3.3).

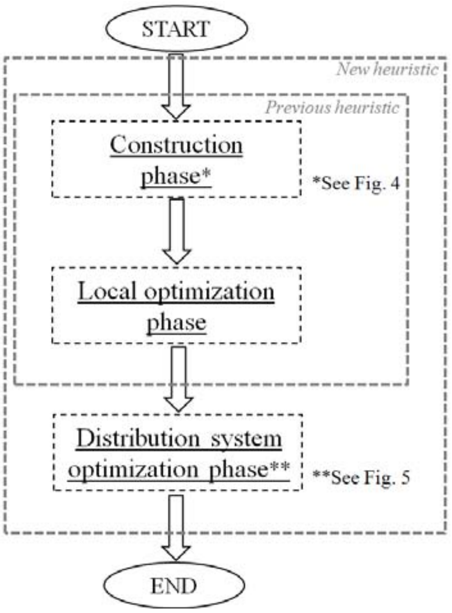

Fig. 3 – Main structure of the enhanced deterministic algorithm

3.1 Internal functions

The internal functions used in algorithm description are hereby reported. Some of these functions were modified from those utilized in ref. [11] in order to make them easily adapted for the GRASP based algorithm described in Section 4.

$P(m)$	Set of points of microgrid m
$DP(m)$	Set of demand points of microgrid m

MS(*s*)	Set of microgrids of solution *s*
S(*M*)	Solution composed by microgrids of set *M*
CM(*m*)	Cost of microgrid *m*, including all components of the generation and distribution systems.
CS(*s*)	Cost of solution *s*. $CS(s)=\sum_{m\in MS(s)} CM(m)$
R(*m*)	Generation point (root) of microgrid *m*
A(*m*)	Set of arches of microgrid *m*
L(*x,y*)	Distance between point *x* and *y*
LA(*a*)	Length of arch *a*
LPA(*x,a*)	Minimum distance between point *x* and arch *a*
LPM(*x,m*)	Minimum distance between point *x* and microgrid *m* If $\lvert P(m)\rvert = 1$ then $LPM(x,m)=L(x,R(m))$ else $LPM(x,m)=\min_{a\in A(m)} LPA(x,a)$
LC(*m1,m2*)[5]	Estimation of the cable extension required to connect microgrids *m1* and *m2*. $LC(m1,m2)=\delta\cdot\min\left(\min_{x\in P(m1)} LPM\left(x,m2\right),\ \min_{x\in P(m2)} LPM\left(x,m1\right)\right)$
BED(m)	Break Even Distance (*BED*) of microgrid *m*. It represents the maximum distance at which microgrid *m* could be reliably connected to another microgrid or to a no-demand generation point. Given *UCC* the lowest unitary cable cost [\$/m] and *CC*(*m*) the total electric cable cost of microgrid *m*, $BED(m)=\dfrac{CM(m)-CC(m)}{UCC}$
B(*m*)[6]	Set of branches of microgrid *m*
MB(*B*)	Microgrid composed by the set of braches *B*
DU(*a,b*)	Set of users part of branch *b* that are downstream arch *a* (the electric energy they receive pass through arch *a*)
PD(*u*)	Electrical power demand of user *u*
AB(*b*)	Set of arches of branch *b* sorted in a decreasing order by *PF(a)*, i.e. the product of arch length and the power flow circulating by it. For each *a* ∈ *AB(b)*, the parameter *PF(a)* is calculated as $PF(a)=L(a)\cdot\sum_{u\in DU(a,b)} PD(u)$
CB(b)[7]	Cost of the cables of branch *b*.
BD(*a,b*)	Set of 2 branches {$BD_1(a,b)$, $BD_2(a,b)$} resulting from removing arch *a* of branch *b*. Branch $BD_1(a,b)$ is composed by arches connecting all users *DU(a,b)*, while branch $BD_2(a,b)$ is composed by the arches connecting the rest of users
Split(*b*)	Set of (1 or 2) branches that results after trying to eliminate one by one all arches of *b*. The function stops when a division is accepted because the

---

[5] δ is a coefficient used to take into account possible slight differences between microgrids' distance and real cable extension. In the heuristic proposed in [11] δ=1 was assumed. In this study a value of δ=0.85 is considered in order to increase the possibility of connecting microgrids and thus to enlarge the search space of the algorithm.

[6] A branch is defined by the arches and the points (always including the generation point) of a microgrid that are downstream the same point, i.e. the electric energy they receive pass through the same arch connecting the generation point and a child of it (see Fig. 2).

[7] Cable connections within a branch follow a radial tree-scheme and are realized so that cable length is minimized using the classical shortest connection network algorithm [18]. The cable type with the minimum cost that fulfills with the maximum permitted voltage drop and the maximum flowing intensity is selected.

distribution system cost is reduced. If no division is accepted then the function returns *b*. The algorithm of this function is reported in the following.

```
For ($a \in AB(b)$)
    If $CB(BD_1(a,b)) + CB(BD_2(a,b)) < CB(b)$ then
        return $\{BD_1(a,b), BD_2(a,b)\}$
    EndIf
EndFor
return $\{b\}$
```

ImproveCableCost(m)

Function that tries to divide all the branches of microgrid *m* into smaller ones in order to reduce the distribution system cost. For each branch the following steps are carried out:

- It calculates the cost of dividing the branch into 2 smaller ones, eliminating one arch of the branch. All the arches are tried to be eliminated.
- If the cost of the 2 new branches is lower than the initial branch cost then the sub-division is accepted. Therefore the same subdivision process is carried out for the resulting 2 branches.
- The procedure stops when no more subdivision is accepted.

Let *DB* be the set of branches to be divided, *b* be the current branch that is tried to be divided and *B** be the set of least cost branches. The detailed algorithm of this function is described in the following.

```
Initialize variables: $B^* = \emptyset$; $DB = B(m)$;
While ($DB \neq \emptyset$)
    $b$ = first element of $DB$; $DB = DB \setminus \{b\}$
    If ($Split(b) = \{b\}$) then $B^* = B^* \cup \{b\}$
    else $DB = DB \cup Split(b)$
EndWhile
Return $MB(B^*)$[8]
```

$MR(m, x, r)$	Microgrid composed by $DP(m)$ demand points with generation in point x. Cable length is firstly minimized using the shortest connection network algorithm [18]. If r = true: Cable cost is then improved utilizing the *ImproveCableCost(m)* function. If r = false: Cable cost is not improved.
$MU(m1,m2, r)$	Microgrid (mu) that results after connecting (according to Prim's algorithm [18]) all demand points of microgrids $m1$ and $m2$. Therefore, $DP(mu) = DP(m1) \cup DP(m2)$ If r = true (cable cost is improved): The cable cost of mu is obtained utilizing the *ImproveCableCost(mu)* function; the root of microgrid mu is the one that leads to the lower cost between the root of $m1$ and the root of $m2$: if $CM(MR(mu,R(m1),\text{true})) < CM(MR(mu,R(m2),\text{true}))$ then $mu = MR(mu,R(m1),\text{true})$ otherwise $mu = MR(mu,R(m2),\text{true})$.

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[8] In this function the generation point of microgrid *m* does not change. Thus $R(MB(B^*)) = R(m)$

If r = false (cable cost is not improved): $R(m2)$ is selected as the root of mu only if it leads to a lower microgrid cost and has a HPI[9] higher than $R(m1)$):
if $CM(MR(mu,R(m2),\text{false})) < CM(MR(mu,R(m1),\text{false}))$ and $HPI(R(m2)) > HPI(R(m1))$ then $mu = MR(mu,R(m2),\text{false})$ otherwise $mu = MR(mu,R(m1), \text{false})$.

SelectM(*m, M*) Returns the microgrid mc to be connected to microgrid m. mc is selected from set M of microgrids. The selected microgrid mc is

$$mc = \underset{z\in M \left| LC(z,m)\leq max\left(BED(z),BED(m)\right)\right.}{\arg\max} \left(\left(CM\left(m\right)+CM\left(z\right)\right)-CM\left(MU\left(m,z,\text{true}\right)\right)\right)$$

IGC(*s, ND*) Returns the solution with generation in the best (low cost) demand point of each microgrid or in a no-demand point of set ND. For every microgrid m of solution s, the point x (part of the microgrid m or of set ND) that, if selected as the root, leads to the minimum microgrid cost is defined as microgrid generation point. In this function, set ND does not include no-demand points that are already the generation point of another microgrid part of solution s.

$$IGC(s,ND) = S\left(\bigcup_{m\in MS(s)} MR\left(m,\ \underset{x\in P(m)\cup ND}{\operatorname{argmin}} \left(CM\left(MR\left(m,x,\text{true}\right)\right)\right), \text{true} \right) \right)$$

3.2 Construction phase

The main steps of the construction phase are shown in Fig. 4. Starting from the solution considering all independent generation points, the algorithm constructs the microgrids extending them as much as possible if solution cost decreases. The microgrids are subsequently constructed in two iterative cycles (Fig. 4):

1) Cycle 1: New microgrid construction iteration starts. The grid generation point of the (current) microgrid is firstly selected (STEP1) and then it starts cycle 2 in which the microgrid is extended.
2) Cycle 2: In each iterative step a microgrid (composed by one or more users) is tried to be connected to the current microgrid depending on certain criterion (STEP2). If the new microgrid has a lower cost than the two previous ones then the connection is accepted and Cycle 2 restarts. If the connection is not accepted then a new Cycle 1 starts.

The algorithm ends when all the demand points of the community are part of a created microgrid, i.e. a microgrid that was already tried to be extended.

---

[9] $HPI(x)$ is the Hybrid Potential Indicator of a certain point x that is calculated according to [19]. It is a resource indicator that considers the multiple renewable resources available in the area: higher the $HPI(x)$ higher the resource(s) potential in point x.

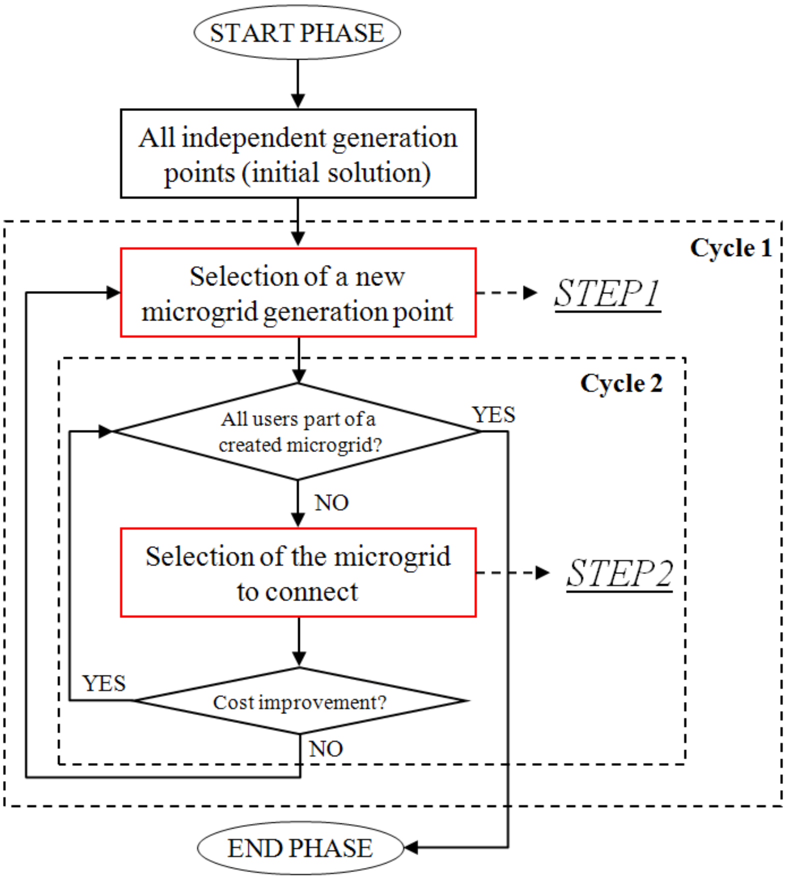

Fig. 4 – Main structure of the construction phase. STEP1 and STEP2 indicate the selection steps.

The "selection steps" (STEP1 and STEP2 of Fig.4) are the most critical parts of the algorithm and are defined by two characteristics: the pool of possible candidates (PE_1, PE_2, respectively) and the indicator or heuristic function (HF_1, HF_2, respectively) used to rank the set *PE* and select the best candidate.

Regarding STEP1, the pool of possible candidate elements (PE_1) from which the microgrid generation point could be selected is the union of the sets of demand (*D*) and no-demand points (*ND*), not selected as a grid generation point in a previous iteration of cycle 1 (equation 3.1). As the number of initial no-demand points in an area could be considerably high, e.g. wind generation points are generally presented in form of a wide spatial grid with a spacing of 50 or 100 m, an "initial filter", proposed in ref. [11], is firstly applied to pre-select most promising generation locations taking into account resource and demand distributions.

- $PE_1 = D \cup ND$ (3.1)

The heuristic function (HF_1) to rank the elements of the set PE_1 is the Grid Generation Score (*GGS*): an indicator that, based on demand and resource distributions, evaluates how much a certain point has the adequate characteristics for being the generation point of microgrid composed by multiple users (for more details see ref. [19]). The point with the highest HF_1 (equation 3.2) is selected:

- $HF_1(x) = GGS(x) \quad \forall x \in PE_1$ (3.2)

Regarding STEP2, i.e. the selection of the microgrid to connect, being *m* the current microgrid in expansion, the pool of possible candidates (PE_2) is composed by all microgrids of the current solution *s* (excluding *m*) located at a distance from *m* lower than their Break Even Distance (*BED*) (equation 3.3).

$$PE_2 = \{ mc \in MS(s) \setminus \{m\} \mid LC(mc, m) \leq BED(mc) \} \tag{3.3}$$

The microgrid *y* that is tried to be connected to microgrid *m* could be selected in the following three different ways, adapted from ref. [11]: HF_{2a}, HF_{2b} and HF_{2c} (equations 3.4, 3.5 and 3.6).

4. By distance (the element with the lowest HF_{2a} value is selected):

$$HF_{2a}(y) = LC(y, m) \qquad \forall y \in PE_2 \tag{3.4}$$

5. By *NGS*, *IGS* and distance (the element with the highest HF_{2b} value is selected):

$$HF_{2b}(y) = \frac{\max\limits_{py \in DP(y)} \left(1 + NGS(py) - IGS(py); 0.1\right)}{LC(y, m)} \qquad \forall y \in PE_2 \tag{3.5}$$

   The *NGS* (No-generation Score) and the *IGS* (Independent Generation Score) are indicators that evaluate how much some a-priori characteristics of a point indicate that it should be a no-generation point (*NGS*) or an independent generation point (*IGS*) (for more details see ref. [19]). As *NGS* and *IGS* can range from 0 to 2, a minimum value of the numerator is defined (0.1) in order to obtained always positive values of the HF_{2b}.

6. By savings (the element with the highest HF_{2c} value is selected):

$$HF_{2c}(y) = \left(\left(CM(m) + CM(y)\right) - CM\left(MU\left(m, y, \text{false}\right)\right)\right) \quad \forall y \in PE_2 \tag{3.6}$$

As the heuristic function that leads to the best results is not always the same [11], the algorithm is launched three times, each time with one of the 3 HF_2, and finally the best found solution is returned.

3.3 Distribution system optimization phase

In order to reduce the distribution system cost (by means of utilizing less expensive cables and thus reducing the total cost), we propose to add a “Distribution system optimization phase” at the end of the previous “construction” and “local optimization” phases (Fig. 3). This new phase structure is shown in Fig. 5: firstly the branches of the microgrids of a previously obtained solution are tried to be subdivided, i.e. “Branches subdivision” (sub-Section 3.3.1) and then obtained microgrids are iteratively tried to be interconnected, i.e. “Microgrids interconexion” (sub-Section 3.3.2).

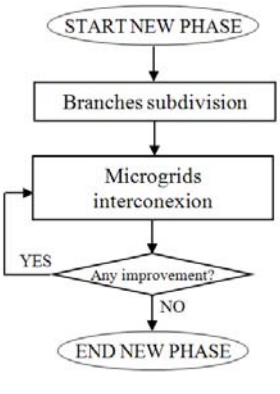

Fig. 5 – Main structure of the distribution system optimization phase

3.3.1 Branches subdivision

This step aims to improve the distribution system cost of the microgrids of the current solution by means of trying to subdivide the branches. Therefore, the function "*ImproveCableCost()*" is applied to every microgrid, as shown in the following.

Parameters

is	Initial solution
*M**	Set of least cost microgrids

Algorithm

1. $M^* = \bigcup_{m \in MS(is)} \mathit{ImproveCableCost}\ (m)$
2. Return $S(M^*)$

3.3.2 Microgrids interconnection

During this step the microgrids of the current solution are tried to be interconnected. For each microgrid *m* the following sub-steps are carried out:

- The microgrids located at distance to the microgrid (*m*) lower than their Break-Even Distance are tried to be connected (separately) to *m*. Next, in order to improve the distribution system, the "*ImproveCableCost()*" function is applied to each newly obtained microgrid. The microgrid *mc* that leads to the highest savings is selected.
- If the connection between microgrids *m* and *mc* decreases the cost of the solution then the two microgrids are connected and the algorithm tries to connect another microgrid to the latter obtained microgrid.
- This process stops when the connection is rejected (no cost improvement is obtained).

A detailed description of the procedure is reported in the following.

Parameters

is	Initial solution
IM	Set of microgrids part of the initial solution *is* sorted by the number of connected points in descending order (in case of tie, by total cable length in descending order)
ND	Set of no-demand points pre-selected by the initial filter [11] as possible generation points
RM	Set of remaining microgrids that should be tried to be interconnected with the other microgrids
m	Current microgrid that is tried to be interconnected to the other microgrids
SM	Set of remaining microgrids that could be connected to *m*
mc	Selected microgrid to be connected to *m*
s	Current solution
sn	New solution obtained
AcceptCon	Boolean variable that indicates if the connection of microgrids *m* and *mc* is accepted or not
Continue	Boolean variable value that indicates if a new connection will be tried or not
*s**	Least cost solution

Algorithm[10]

```
Initialization: $RM = IM; s^* = is;$
While ($RM \neq ø$)
  $m$ = first element of $RM$; $RM = RM \setminus \{m\}$; $SM = MS(s^*) \setminus \{m\};$
  $s = s^*;$ $Continue = \exists mc \in SM \,|\, LC(mc,m) \leq \max\big(BED(mc), BED(m)\big)$
  While ($Continue$ and $SM \neq ø$)
    Select the microgrid to be connected to $m$: $mc = SelectM(m, SM)$
    $m = MU(m, mc, \text{true})$; $SM = SM \setminus \{mc\};$ $sn = S(SM \cup \{m\})$
    Connection acceptance criterion: $AcceptCon = (CS(sn) < CS(s))$
    If ($AcceptCon$) then $s = sn$; $s^* = sn$; $RM = RM \setminus \{mc\}$; EndIf
    $Continue = AcceptCon$ and $\exists mc \in SM \,|\, LC(mc,m) \leq \max\big(BED(mc), BED(m)\big)$
  EndWhile
EndWhile
Improve generation cost: $s^* = IGC(s^*, ND)$
Return $s^*$
```

4. GRASP based algorithm

The enhanced deterministic heuristic described in Section 3 improves the performance of the previous deterministic heuristic proposed by ref. [11], with a minimum increase in the computational time, as verified in sub-Section 5.2. Thus, that enhanced deterministic heuristic (from now on referred to as the "deterministic heuristic") is considered as the starting point for the development of the GRASP based algorithm described in this Section. The deterministic heuristic is a greedy procedure in which a single solution is obtained in two main stages (Fig. 6): solution construction (construction phase) and solution improvement (local optimization and distribution system optimization phases). However, the solution space of a problem, i.e. the set of all possible feasible solutions, is generally composed by multiple "basins of attraction" (Fig. 6), i.e. the set of initial solutions which, after applying the improvement phase, converge to a certain solution [20]. Starting from an initial (constructed) solution (point "0") and applying the improvement phase will forcedly lead to the basin of attraction of the valley at which point "0" belongs (point "1"). Point "1" is a local optimum, i.e. a solution that is optimal within all solution analyzed by the local search procedure; however this does not guarantee the quality of this solution in comparison with the global optimum, i.e. the best of all feasible solutions, that may be located in a different valley.

In the last few decades, various meta-heuristic procedures have been developed in order to better explore the solution space, escape from local optima and thus improve encountered solutions [13]. An effective meta-heuristic to enlarge the search space introducing randomness in a deterministic greedy heuristic is the GRASP, Greedy Randomized Adaptive Search Procedure [14]. GRASP based methods have been successfully applied to many location optimization problems [15], such as the capacitated plant location problem

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[10] As shown in Fig. 5, this algorithm is part of an iterative process.

[16], which has many similarities with the AVEREMS problem (see ref. [11]). A GRASP is a multi-start process, in which each iteration consists of two phases (Fig. 7): solution construction, in which a feasible solution is produced using a randomized greedy algorithm, and solution improvement (or local search) which starts at the constructed solution and applies iterative improvement until a local optimum is found. Repeated applications of the randomized construction procedure yields diverse starting solutions for the local search and the best overall solution obtained in the process is kept as the result (Fig. 6).

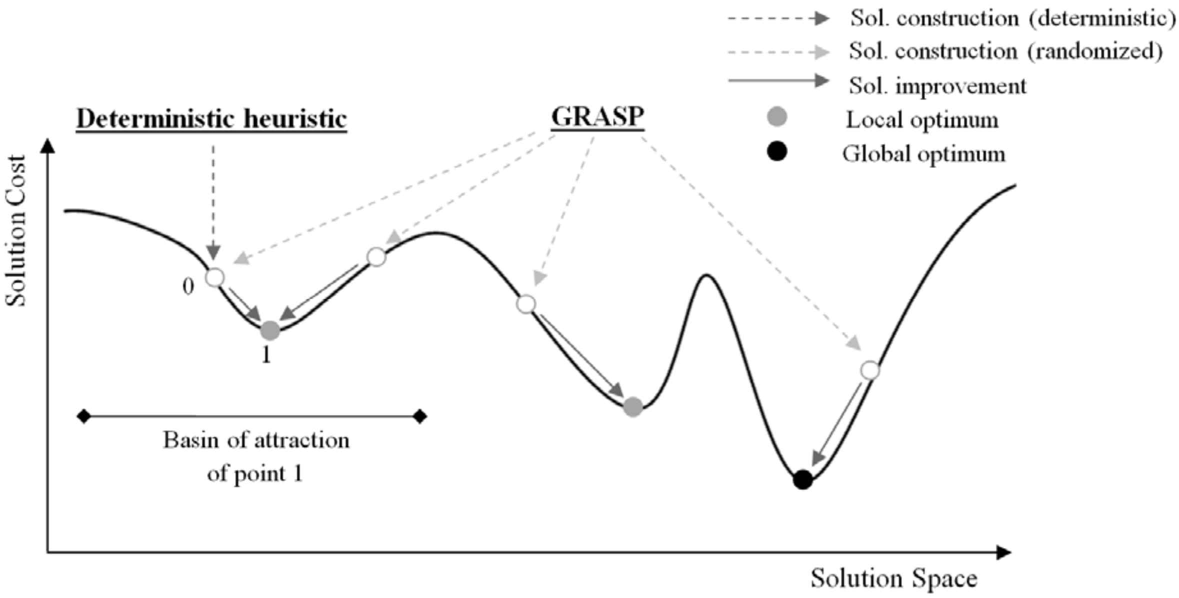

Fig. 6 – Main stages of the deterministic and GRASP algorithms in the solution space of a minimization problem.

We propose the development of a GRASP based algorithm in which each iteration is composed by the launch of an algorithm based on the deterministic heuristic (Fig. 3), but in which the construction phase is randomized (Fig. 7). As stopping criterion, a maximum calculation time or a maximum number of iterations is usually defined.

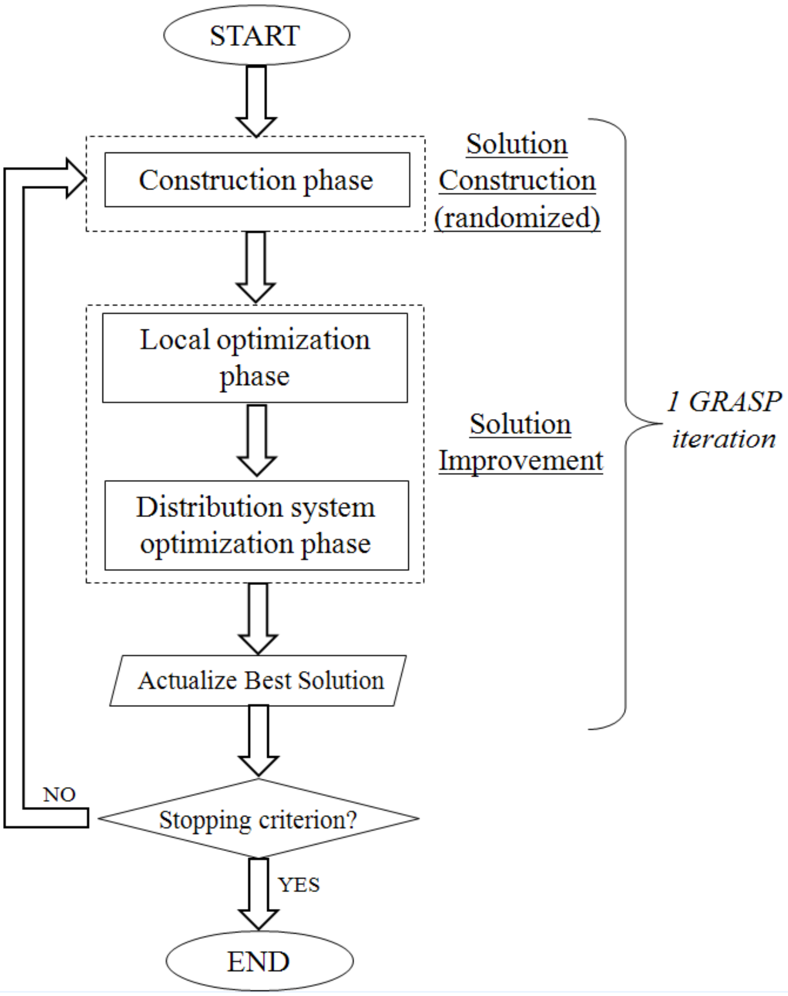

Fig. 7 – Main structure of the GRASP based algorithm

In the following, we describe the new randomized solution construction (sub-Section 4.1) and the different proposed algorithm versions (sub-Section 4.2).

4.1 Randomized construction phase

The randomness of the GRASP is introduced in the solution construction phase in order to generate a wide range of different initial solutions and therefore improve the exploration of the solution space (Fig. 6). Assuming that a solution is composed by different elements that could be ranked by a heuristic function, the randomness can be introduced in the way these elements are selected [14]. As stated in sub-Section 3.2, microgrids can be seen as the different elements of a solution that are subsequently constructed in two iterative cycles (Fig. 4). Within each cycle there is a "selection step" (STEP1 and STEP2) in which the elements are ranked by a heuristic function and then the best ranked element is selected. Instead of selecting the best element, two restricted candidate lists (RCLs) could be used in STEP1 and STEP2 in order to introduce randomization:

1) *RCL1*: list for the selection of the microgrid generation point (STEP1).
2) *RCL2*: list for the selection of the microgrid that is tried to be connected (STEP2).

In the classical GRASP implementation [14], a single RCL is used. Hereby two RCLs are considered in order to increase the randomization effect, enhance the variability of the constructed solutions and thus enlarge the exploration of the solution space.

The main characteristics of the RCLs are: the pool of possible candidates, the size (nº of elements) of the RCL, the heuristic function and the selection procedure. These characteristic for RCL1 and RCL2 are reported in Table 1 and next described:

a) The pool of possible candidates for STEP1 and STEP2 (respectively PE_1 and PE_2) are defined in sub-Section 3.2 (equations (3.1) and (3.3)).

b) Regarding the size, the number of best ranked elements (according to their heuristic function) to be included in the RCL could be defined as [21]:

$$SE = \max\left(\left\lceil \alpha \cdot |PE| \right\rceil, 1\right) \text{ where } 0 \le \alpha \le 1 \qquad (4.1)$$

Note that if $\alpha = 0$ then the selection is deterministic (i.e. the best ranked element is always selected), while as α increases higher will be the randomness of the selection (with $\alpha = 1$ the highest randomness is achieved). The appropriate choice of the value of parameter α is clearly critical and relevant in order to achieve a good balance between computation time and solution quality [22]. Parameter α will be calibrated for both RCL1 and RCL2 (sub-Section 5.3.1).

c) The heuristic functions (*HF*) used in STEP1 and STEP2 are defined in sub-Section 3.2. There is a single HF_1 for STEP1 (equation (3.2)), while there are three possible HF_2 (HF_{2a}, HF_{2b}, HF_{2c}, defined in equations (3.4), (3.5) and (3.6)) for STEP2.

d) Regarding the selection procedure, in the original GRASP the selection of an element from the RCL is done in a uniform random way: all elements of the list have the same probability to be chosen [14]. However, later studies showed that better results can be achieved by a random biased selection, in which the probability of selecting a certain element is proportional (or inversely proportional) to its heuristic function [23], [24]. Therefore, being HF_i the value of the heuristic function for element *i*, the selection probability p_i of element *i* from a RCL is calculated as:

- Proportional selection (P): $p_i = \dfrac{HF_i}{\sum_{y \in RCL} HF_y}$ (4.2)
- Inversely proportional selection (IP): $p_i = \dfrac{1/HF_i}{\sum_{y \in RCL} 1/HF_y}$ (4.3)

The set *RCL* is composed by the *SE* best ranked elements of the pool of possible candidates (*PE*). Elements are sorted by their *HF* value in a decreasing or increasing order in the case of respectively proportional or inversely proportional selection.

Table 1 – Characteristics of RCL1 and RCL2

Characteristic	RCL1 (STEP1)	RCL2 (STEP2)
Elements of the RCL	Grid generation points	Microgrids
a) Pool of possible candidates[a]	PE_{1}: Set of demand and no-demand points not previously selected as a grid generation point	PE_{2}: Set of microgrids (excluding the current microgrid in expansion) located at a distance lower than their BED
b) Size of the RCL[b]	$SE_1 = \max\left(\left[\alpha_1 \cdot \left\|PE_1\right\|\right],1\right)$	$SE_2 = \max\left(\left[\alpha_2 \cdot \left\|PE_2\right\|\right],1\right)$
c) Heuristic function[a] / d) Selection procedure[c]	HF_1 / P	3 alternatives: HF_{2a} / IP HF_{2b} / P HF_{2c} / P

[a] The formal definition of PE_1, PE_2, HF_1, HF_{2a}, HF_{2b}, and HF_{2c} is reported in equations (3.1) to (3.6).

[b] The value of parameters α_1 and α_2 is calibrated in sub-Section 5.3.1.

[c] Regarding selection procedure, P and IP refer respectively to proportional and inversely proportional selection.

4.2 Different algorithm versions

As shown, there are three heuristic functions for STEP2 (HF_{2a}, HF_{2b}, and HF_{2c}). The heuristic function that obtains the best results cannot be defined a-priori. Therefore, we propose to analyze the performance of the following 5 GRASP based algorithm versions:

- GRASP1: HF_{2a} is always applied in each STEP2
- GRASP2: HF_{2b} is always applied in each STEP2
- GRASP3: HF_{2c} is always applied in each STEP2
- GRASP4: HF_{2a}, HF_{2b} or HF_{2c} are randomly selected (with the same probability) in each STEP2 of the construction phase.
- GRASP5: HF_{2a}, HF_{2b} or HF_{2c} are alternatively applied in each GRASP iteration.

Furthermore, another algorithm version (GRASP0) in which the selection of the microgrid generation point (RCL1) and the selection of the microgrid to be connected (RCL2) are totally random, i.e. $\alpha_1 = \alpha_2 = 1$ and $HF_1 = HF_2 =$ constant (e.g. 1), is also analyzed in order to evaluate the importance of utilizing good heuristic functions. The performances of these algorithm versions are compared in Section 5.

5. Computational experiment

In the previous Sections, an enhanced deterministic heuristic (Section 3) and then a GRASP based procedure (Section 4) were presented in order to support the design of autonomous community rural electrification projects based on renewable energies considering a combination of independent generation points and microgrids.

Hereby, we carried out a computational experiment in order to analyze the performance of the proposed algorithms. The analyzed instances are firstly described in sub-Section 5.1; then the improvements of the enhanced deterministic heuristic in comparison with the previous one [11] are analyzed (sub-Section 5.2); in sub-Section 5.3 the different GRASP based algorithm versions are calibrated and finally the performance of the best version is evaluated in comparison with the procedure available in literature (sub-Section 5.4). All calculations were done on a PC Intel Core 2 i7-2600 3.4 GHz with 8 GB of RAM.

5.1 Analyzed instances

The same instances utilized in ref. [11] are used: the complete input data are available at https://www.ioc.upc.edu/EOLI/research/. The instances were randomly generated based on the characteristics of the following 5 real rural electrification projects: El Alumbre (Peru), Alto Perú (Peru), Achada Leite (Cape Verde), El Roblar (Nicaragua) and Sonzapote (Nicaragua). Real projects resource data are utilized in order to generate the instances: solar resource was estimated by NASA database [25], while the wind resource map of the area (with a grid spacing of 100 m) was obtained using a micro-scale wind flow model [7]. The electricity requirements of each user (household) are 420Wh/day and 300W of energy and power demand respectively. Regarding electrical equipments, the following data were considered:

- Wind turbines (4 types): nominal power: 100 W to 2000 W; cost (including controllers): \$1394 to \$8732.
- PV panels (3 types): nominal power: 50 W to100 W, cost: \$451 to \$821.
- PV controller (3 types): maximum power: 50 W to 100 W, cost: \$67 to \$95.
- Batteries (4 types): capacity: 1500 Wh to 3000 Wh; cost: \$225 to \$325; efficiency 85%; maximum discharge rate: 0.6; autonomy: 2 days.
- Inverters (4 types): maximum power: 300 W to 3000 W; cost: \$377 to \$2300; efficiency 85%.
- Electric cables (2 types): cost: \$4.9/m and \$5.1/m; resistance: 2.71 and 2.15 Ω/km; maximum intensity: 89 and 101 A; nominal voltage: 220 V; minimum voltage: 220 V; maximum voltage: 230 V.
- User consumption meter: cost: \$50 (installed only in microgrids composed by multiple users).

The instances have a variable number of users (ranging from 10 to 90) and, regarding users' distribution, they were randomly generated considering two different concentrations (last row of Table 2). According to the characteristics described in Table 2, two set of instances were generated: a "training set" of 90 instances for the calibration of the internal parameters used by the developed procedures and a "test set" of 450 instances for comparing the performance of the developed procedures.

Table 2 – Characteristics of the analyzed instances

	Community	El Alumbre	Alto Perú	Achada Leite	El Roblar	Sonzapote
Type of real project	Project name	C1	C2	C3	C4	C5
	Area [km^2]	3.5 x 3.5	1.5 x 3.5	2 x 2	3 x 3	4 x 4
	Solar Resource [PSH]	4.3	4.3	4.8	4.2	4.3
	Wind speed [m/s]: min and max values of the map	2 – 6.5	1.5 – 4	1.1 – 7.5	1 – 10.2	0.9 – 9.7
Nº of users		10, 20, 30, 40, 50, 60, 70 80, 90				
Concentration of users		Low (25% of the users in 20% of the area) High (50% of the users in 20% of the area)				

5.2 Performance of the enhanced deterministic heuristic

The solutions of the enhanced deterministic heuristic described in Section 3 ("enhanced deterministic heuristic" or "EDH") are compared with those obtained by the previous deterministic heuristic [11] (“initial deterministic heuristic” or “IDH”). The results of the comparison between the 2 algorithms in the test set of 450 instances are shown in Table 3: columns 3 to 6 show the mean solution cost (“cost”) and mean computation times (“time”) of the IDH and the EDH for different groups of instances; columns 7 shows the % of the difference between mean solution costs; column 8 and 9 indicate respectively the number of instances (in percentage) in which EDH improves the IDH of more than 1% and vice versa (in the rest of instances the differences between solutions of the 2 algorithms are lower than 1%).

The improvement of the enhanced heuristic is highly related with the number of users of the community (Table 3), i.e. the complexity of the instance to be solved. The effect of including the cable optimization phase is almost null for communities up to 30 users in which initial heuristic were found to be close to the optimal, according to ref. [11]. The improvement of the EDH in comparison with the IDH increases rapidly as the number of users increases: for communities of more than 60 users significant improvements (more than 1%) of the EDH are found in 20% of the instances, whereas significant improvements of the IDH were found in less than 3% of the instances. The total mean solution costs of the IDH and the EDH are 87615$ and 87392$ respectively: the slight increase in calculation time is compensated by the solution improvement obtained by the enhanced deterministic heuristic.

Table 3 – Comparison between the initial (IDH) and the enhanced (EDH) deterministic heuristic

		IDH		EDH		Comparison		
		Cost [US$]	Time [s]	Cost [US$]	Time [s]	Difference	EDH > 1%	IDH > 1%
Project type	C1	89508	23.4	89426	28.8	0.06%	5.6%	3.3%
	C2	97943	29.4	97908	34.3	0.03%	4.4%	2.2%
	C3	82258	14.4	81470	23.7	0.74%	28.9%	4.4%
	C4	84670	19.3	84543	25.3	0.07%	5.6%	2.2%
	C5	83695	29.8	83615	33.5	0.02%	5.6%	3.3%
N° of users	10-30	37747	5.0	37744	5.3	0.01%	1.3%	1.3%
	40-60	88492	19.9	88345	23.4	0.14%	8.7%	5.3%
	70-90	136605	44.9	136089	58.7	0.40%	20.0%	2.7%
Users concentration	low	88590	22.8	88381	28.2	0.17%	8.4%	0.9%
	high	86640	23.7	86403	30.1	0.19%	11.6%	5.3%
Total		87615	23.3	87392	29.1	0.18%	10%	3.1%

5.3 Selection of best GRASP based algorithm version

As stated in sub-Section 4.2, different algorithm versions (based on the GRASP) should be analyzed, depending on the heuristic function utilized in the selection of the microgrid that is tried to be connected. In this Section all versions are firstly calibrated (Section 5.3.1) and then performances are compared in order to select the best one (Section 5.3.2).

5.3.1 Calibration of the algorithms

As stated in sub-Section 4.2, the value of parameter α, i.e. the ratio of possible candidates included in the RCL, is highly relevant in order to achieve a good balance between computational time and solution quality of a GRASP. Therefore, the parameters $\alpha_1 = 0$, 0.2, …, 1 and $\alpha_2 = 0$, 0.2, …, 1 are calibrated, i.e. all combinations of values are tried, for the different algorithm versions on the “training set” of 90 instances. A computational time of 800 s is considered for each instance. The combinations of values that lead to the best (mean lowest cost) solutions are reported in Table 4.

Table 4 – Different GRASP versions with calibrated values of α_1 and α_2

Algorithm version	Selection of the microgrid generation point (RCL1)		Selection of the microgrid that is tried to be connected (RCL2)	
	HF_1	α_1	HF_2	α_2
GRASP1	HF_1	0.2	HF_{2a}	0.6
GRASP2	HF_1	0.6	HF_{2b}	0.8
GRASP3	HF_1	0.6	HF_{2c}	0.2
GRASP4	HF_1	1	Randomly selected by HF_{2a}, HF_{2b}, HF_{2c}	0.2
GRASP5	HF_1	[a]	HF_{2a}, HF_{2b}, HF_{2c} are alternatively utilized	[a]

[a] As GRASP5 consists in alternatively implementing one iteration of GRASP1, one of GRASP2 and one of GRASP3, the same α_1 and α_2 values of these GRASP versions are considered for GRASP5.

5.3.2 Comparison of different algorithm versions

Hereby, the 5 algorithm versions (GRASP1 to GRASP5) together with GRASP0 are compared and their results on the “test set” of 450 instances are shown in Fig. 8 and Table 5. Fig. 8 shows the convergence curves, i.e. the evolution of the cost of the best solution obtained by each version over the computational time. Each point of these curves is the mean value of the solution costs in the 450 instances at different computational times. For each GRASP version, Table 5 shows the mean solution cost obtained with 3600 s (column 2) and the percentage of instances for which each version finds a solution that is less than 1% worse than the best solution obtained by the 6 versions (column 3).

The version that does not use any heuristic function (GRASP0) obtains the worst results: its mean solution cost is higher than 87000$ (while all other versions are below 86800$) and its convergence curve is always above all the others. This confirms the importance of utilizing good heuristic functions for the selection of the elements in the RCLs.

The convergence curves of the other algorithm versions (GRASP1 to GRASP5) have a similar pattern: most of the improvement is reached in the first 1000 s (dotted line in Fig. 8) whereas afterwards the curves tend to be horizontal (asymptotes). GRASP1 and GRASP2 obtain better results in comparison with GRASP3, possibly because the calculation for the savings (HF_{2c}) requires longer computational time than the other heuristic functions (HF_{2a} and HF_{2b}). However the versions that utilize the 3 heuristic functions (GRASP4 and GRASP5), taking advantage of the benefits of each one, are better options. GRASP4 (in which the HF utilized in each launch of RCL2 is randomly selected between HF_{2a}, HF_{2b} and HF_{2c}) is the best version: its convergence curve is always below all the others, its final mean solution cost is the lowest one (86666$) and it obtains the best solution in more instances (99.8%) than GRASP5 (99.1%).

Therefore, the version GRASP4 is selected as the proposed solving procedure of this study.

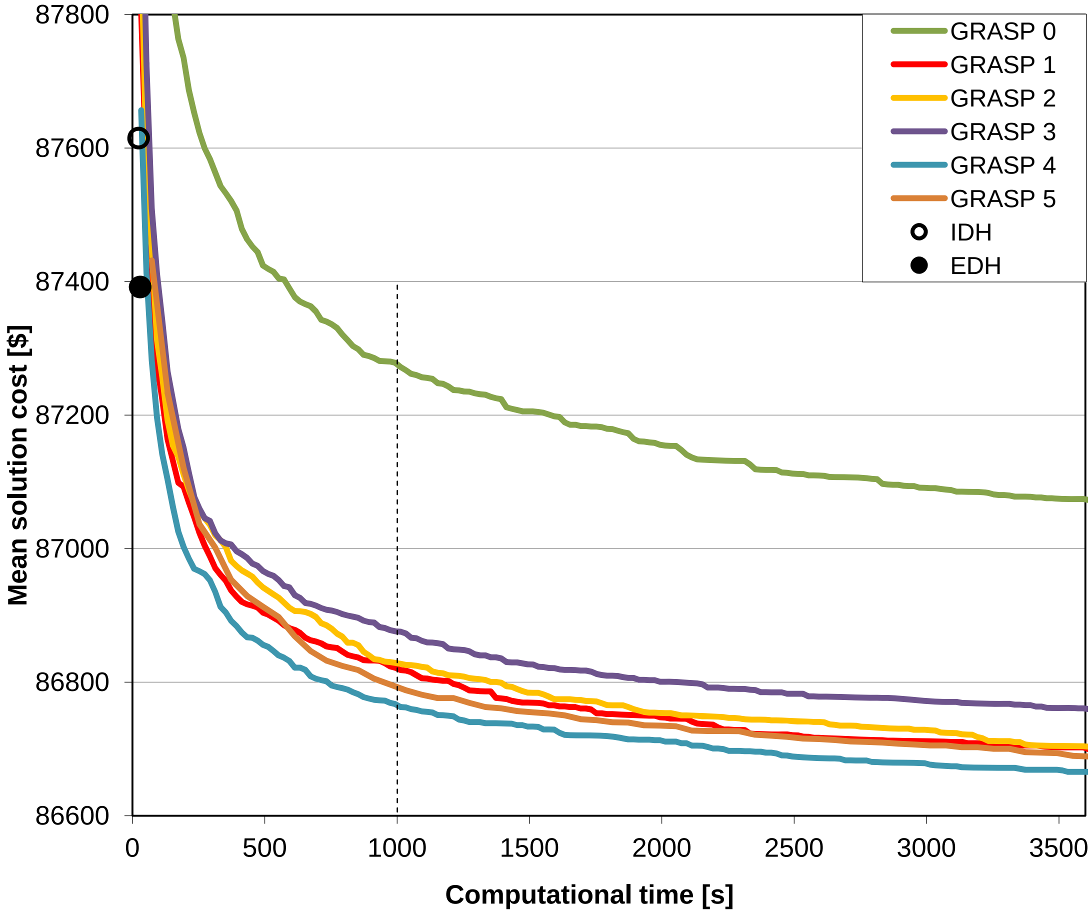

Fig. 8 – Comparison between convergence curves of the different GRASP versions

Table 5 – Comparison between solutions obtained by the different algorithm versions

Version	Mean solution cost [$]	Best solution (within 1%)
GRASP0	87073	87.3%
GRASP1	86700	98.9%
GRASP2	86703	98.4%
GRASP3	86760	97.1%
GRASP4	86666	99.8%
GRASP5	86689	99.1%

5.4 Performance of the GRASP based procedure

As introduced, the only known algorithm that solves the AVEREMS problem thus designing off-grid electrification projects based on renewable energies considering micro-scale resource variations, a combination of independent generation points and microgrids and generation far from demand points is the deterministic heuristic proposed by ref. [11]. The solutions of that algorithm were shown to considerably improve solutions obtained by other procedures that, with some limitations, deal with the same design problem [9], [12]. An enhanced version of that procedure was proposed in Section 3 and improves the performance of the old one, as described in sub-Section 5.2.

Hereby, the solutions of the proposed GRASP based procedure ("GRASP" refers to GRASP4, i.e. the best algorithm version) are now compared with the ones obtained by the enhanced deterministic heuristic (as in sub-Section 5.2 "EDH" refers to the enhanced deterministic heuristic described in Section 3). As shown in Fig. 8, the enhanced heuristic (full black circle) can rapidly obtain a good solution (29 s), slightly better than the one obtained by the GRASP (blue line) in the same computational time (the same solution is reached by the GRASP after 70 s). However, when a higher computational time is available, as it is expected when dealing with the design of a long-term project, the proposed GRASP can considerably enhance the solutions obtained by the EDH.

Table 6 presents the comparison between solutions obtained by the EDH and the GRASP (with a computational time of 3600 s) in the analyzed instances. The EDH and GRASP mean solution costs and computational times are shown in columns 3-4 and 5-6 respectively. Besides the mean difference between both solutions (column 7), the percentage of instances in which GRASP improves EDH solution of more than 1% (column 8) is presented (mention that GRASP improves EDH in all instances except one in which GRASP solution is 0.1% worst than EDH solution).

Table 6 – Comparison between EDH and GRASP procedures

		EDH		GRASP		Comparison	
		Cost [US$]	Time [s]	Cost [US$]	Time [s]	Difference	GRASP > 1%
Project type	C1	89426	28.8	88989	3600	0.4%	13.3%
	C2	97908	34.3	96990	3600	0.7%	37.8%
	C3	81470	23.7	80280	3600	1.1%	45.6%
	C4	84543	25.3	83767	3600	0.7%	30.0%
	C5	83615	33.5	83302	3600	0.3%	11.1%
N^o of users	10-30	37744	5.3	37651	3600	0.2%	7.3%
	40-60	88345	23.4	87697	3600	0.7%	30.7%
	70-90	136089	58.7	134649	3600	1.0%	44.7%
Users concentration	low	88381	28.2	87787	3600	0.5%	22.2%
	high	86403	30.1	85545	3600	0.8%	32.9%
Total		87392	29.1	86666	3600	0.65%	27.6%

The improvement of the GRASP in comparison with EDH depends on the number of users of the community (Fig. 9), the size of community area and the type of users' concentration:

- As the number of users of the instance increases also the differences between EDH and GRASP increase (Fig. 9). For instance of more than 30 users GRASP enhances EDH of more than 1% in more than 20% of the instances. In instances between 70 and 90 users the mean improvement is around 1%.
- As smaller the community area higher the improvement: the lowest improvements (0.4% and 0.3% respectively) are obtained in instances C1 and C5 that where users are dispersed over widest areas (12.25 and 16 km^2 respectively), while highest improvements (1.1%) are obtained in C3 that has the smallest area of just 4 km^2.
- Higher improvements are obtained in instances with higher users' concentration: significant enhancements (more than 1%) are obtained in respectively 22% and 33% of the instances for the low and high users' concentration types.

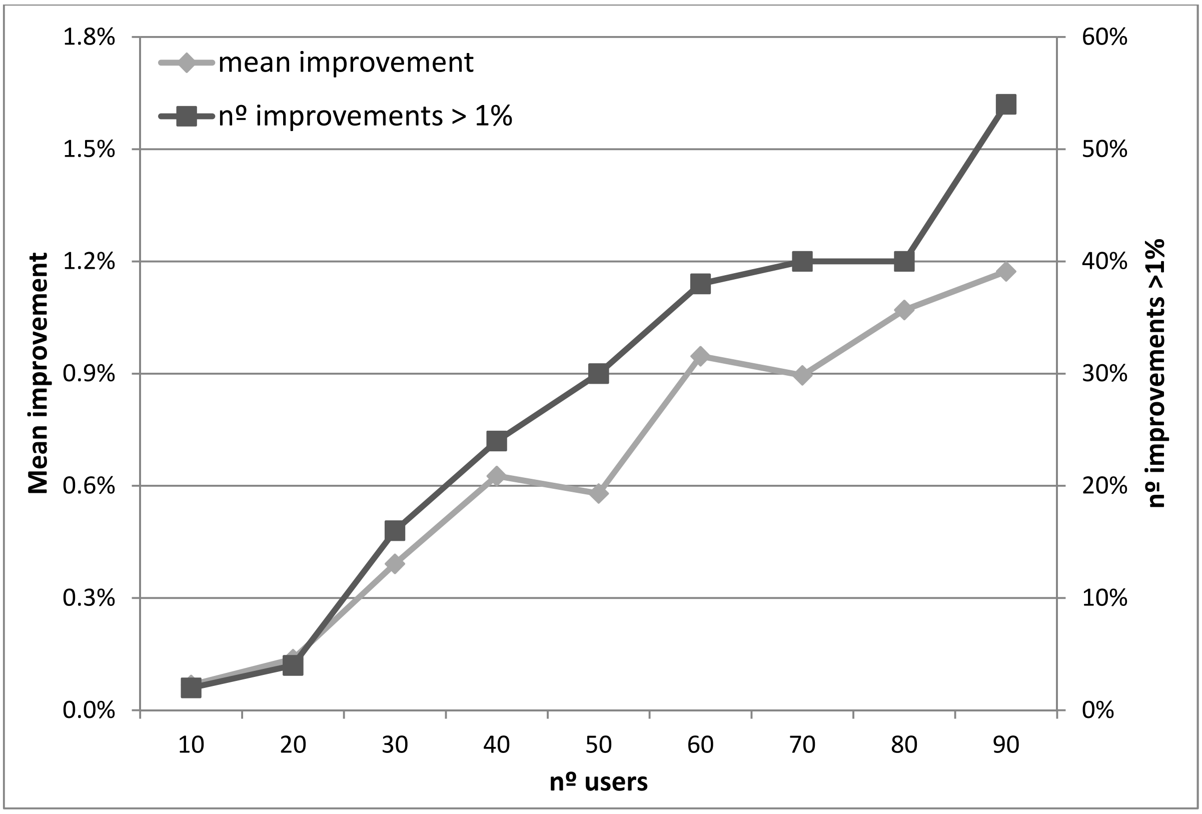

Fig. 9 – Improvement of GRASP in comparison to EDH

Fig. 10 shows the computational time and the number of iterations at which the GRASP reaches the asymptote, i.e. the point at which 90% of the final improvement (after 3600 s) to EDH is obtained. The computational time before reaching the asymptote increases as the number of users increases: in instances up to 60 users the asymptote is reached in less than 600 s. However, even in instances of 90 users, 90% of the final improvement is obtained in slightly more than half of the computational time (2000s over 3600s). This indicates that a computational time of 1 hour can be considered sufficient to get the most out of the GRASP in the analyzed instances.

Regarding the number of iterations before reaching the asymptote, Fig. 10 shows that this value is not that affected by the number of users of the instances. In most cases, the asymptote is reached after between 50 and 200 iterations. Thus when applying the algorithm for the design, a maximum number of iteration can be established as a stopping criterion of the GRASP based algorithm: a value above 200 iterations seems to be adequate in order to get the most out of the algorithm.

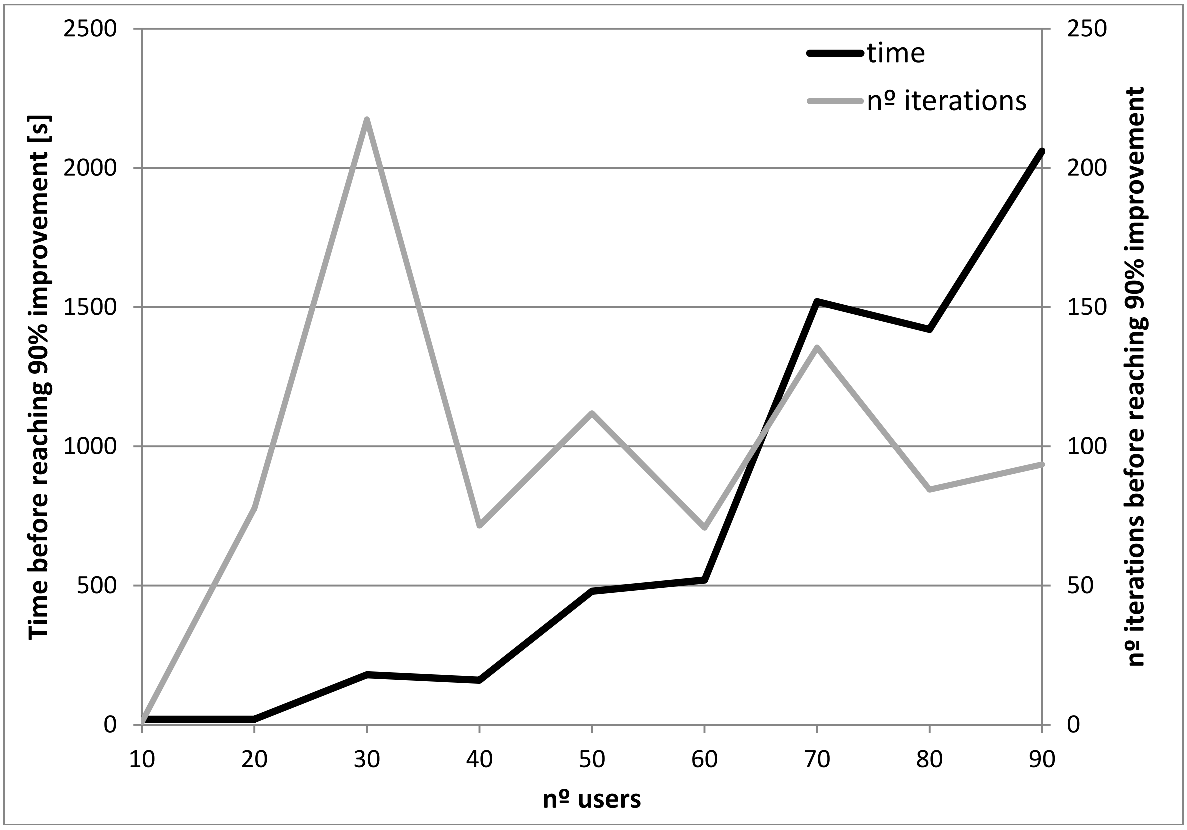

Fig. 10 – Computational time and nº of iterations after which GRASP reaches the 90% improvements in comparison to EDH

6. Conclusions

This study presents an enhanced deterministic heuristic and a meta-heuristic procedure to design rural communities' off-grid electrification projects based on wind and solar energies considering micro-scale resource variations, possible generation location in every point of a certain area and multiple microgrids.

Firstly, some enhancements to an existing deterministic algorithm proposed in a recent publication are presented. The new procedure improves solutions obtained by the previous method with a minimal increase in computational time. Based on this new heuristic, a GRASP based method is proposed in order to escape from local optima where the deterministic heuristic can remain trapped. Different algorithm versions were calibrated and compared in order to select the best one.

The performance of the proposed algorithms was tested on 450 instances from literature, generated according to real projects, with different number of users (from 10 to 90), users' concentrations and available wind and solar resources.

The new deterministic heuristic can rapidly obtain a good solution in less than 1 minute in most analyzed instances. On the other hand, the proposed GRASP based algorithm considerably enhances solutions obtained by the deterministic heuristic with a computational time of 1 hour on a standard PC, a lapse of time generally affordable taking into account the problem to be solved. This improvement tends to increase as the number and the concentration of users increases: significant improvements (higher than 1%) were obtained in more than 30% of the instances bigger than 40 users.

The proposed algorithm is a complete design tool that can efficiently support the design of stand-alone community electrification projects requiring of low computational resources.

Acknowledgements

This paper was supported by the Spanish Ministry of Education (FPU grant AP2009-0738), the MICINN project ENE2010-15509 and co-financed by the Centre for Development Cooperation of the Universitat Politècnica de Catalunya.

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Off-grid community electrification projects based on wind and solar energies: a case study in Nicaragua

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Article submitted to Applied Energy (1st review in progress)

Abstract

Despite various institutional efforts, about 22% of the total Nicaraguan population still do not have access to electricity. Due to the dispersed nature of many rural inhabitants, off-grid electrification systems that use renewable energy sources are a reliable and sustainable option to provide electricity to isolated communities. In this study, the design of an off-grid electrification project based on hybrid wind-photovoltaic systems in a rural community of Nicaragua is developed. Firstly the analysis of the location, energy and power demands of all users of the community is carried out. A detailed resource assessment is then developed by means of historical data, in-situ wind measurements and a specific micro-scale wind flow model. An optimization algorithm is utilized to support the design defining generation (number, type and location of generators, controllers, batteries and inverters) and distribution (electric networks) systems considering the detail of resource variations. The algorithm is modified in order to consider a long-term perspective and a sensitivity analysis is carried out considering different operation and maintenance costs' scenarios. The proposed design configuration combines solar home systems, solar based microgrids and wind based microgrids in order to connect concentrated groups of users taking advantage of best wind resource areas.

1. Introduction

The energy sector in Nicaragua is a critical issue: the country's energy matrix is mainly based on imported fossil fuels (more than 50% of the total net generation) and it has the lowest electrification rate of the Central American region [1]. However, over the past few years, the sector has become a State priority and the country has been undergoing an energy revolution, highly promoting the development of renewable energy projects and increasing electricity coverage [2, 3]. Nicaragua has an important renewable energy potential, especially hydroelectric, geothermal and wind resources, and, by the year 2017, the country's stated goal is to reduce its dependence on non-renewable sources to 6% [2]. On the other side, the social and economical advantages of providing electricity to rural communities in Nicaragua have been clearly demonstrated [4, 5], such as the improvement

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in sanitations facilities, the increase in educational services quality and the development of local business and women employment. Despite various institutional efforts [6], about 22% of the total Nicaraguan population and 40% of the rural population still do not have access to electricity [1, 3].

In the past, most of the efforts in relation to Nicaragua's rural electrification were focused on grid extension [6]. But for a significant part of the country, such grid extension - based solutions are economically and financially unviable due to the remote and dispersed nature of many rural inhabitants. Furthermore, geography poses a major obstacle to the extension of the electric grid, as much of the country is mountainous [5]. For these regions, microgrids, i.e. connecting various demand points to a single generation point, powered by diesel generators represent the historically favoured solution for medium and large off-grid population centres [3]. However, diesel generators have some clear disadvantages and limitations, such as the high and variable fuel cost, the continuous requirement of fuel transportation to the community that could be highly expensive and time consuming specially in rural areas, and the inherent carbon dioxide and other pollutant emissions.

Under these circumstances, stand-alone electrification systems that use renewable energy sources are a suitable alternative to provide electricity to isolated communities in a reliable and pollution-free manner [7, 8]. Moreover, one of their main advantages is that they use local resources and do not depend on external sources, which can promote the long-term sustainability of the projects. During recent years, various programs, such as the Off-grid Rural Electrification Project [9] of the National Sustainable Electrification and Renewable Energy Program [10], have been launched in order to promote rural electrification with renewable energies, mostly small-scale solar and hydropower projects in Nicaragua.

Up to now, small-scale wind technology has been rarely utilized in the country and there is a lack of general knowledge about the technology and its applications [3]. As known, wind resource is highly variable and detailed wind resource studies are required for the correct design of the system [11, 12]. A recent analysis of the market for small wind turbines for off-grid generation in Nicaragua showed that in some areas with good wind resource, e.g. the central highlands, small-scale wind turbines have lower levelized cost of energy, a common parameter for comparing generation technologies, in comparison with solar photovoltaic (PV) power [3]. Anyhow, hybrid systems that combine different resources are generally the most promising generation option [3, 13]. Effectively, the combination of multiple energy resources, such as wind and solar, demonstrated to increase the security of supply and back-ups requirements; many examples of the successful implementation of hybrid systems can be found in literature [8, 13].

Although independent generation systems, i.e. every demand point is generating just for its own consumption, are the common choice when electrifying isolated communities with renewable energies [14, 15], a design configuration that showed to be highly effective is the implementation of microgrids. Microgrids based on renewable energies could lead to a significant decrease in the final cost of the system in comparison with independent generation systems [16], enhance the flexibility of the system and improve equity between user consumptions as all connected users share the same generated energy [17]. In scattered communities with isolated users, the combination of independent generation systems and microgrids is generally the cheapest design configuration [18]. When designing microgrids, the selection of grid generation points and the definition of which points should be connected to a certain micro-grid and which not, are complex tasks, especially when resource (e.g. the wind) is highly variable [12]. Furthermore, a typical community configuration in mountainous context has houses located in the valley while the best wind resource is at the hill/mountain-top: therefore best areas for installing generators could be located far from demand points [16]. Effectively, recent studies showed that locating wind turbines far from demand points could result in a decrease of more than 20% in the initial investment cost of an off-grid electrification project [16].

Therefore, the design of an off-grid renewable energy project considering hybrid systems and distribution microgrids is complex and requires the use of optimization/decision support tools [19]. In the past years, many softwares have been developed in order to define the best combination of energy resources in one point but without designing the distribution through microgrids and taking into account resource spatial variations [19]. Recently, an algorithm for optimizing the design of off-grid electrification projects has been developed that considers the totality of these aspects: hybrid systems, microgrids definition, wind resource spatial variation and generation far from demand points [20, 21].

In this paper we analyze the design of the electrification project of Sonzapote, a rural community located in the central highlands (Boaco province) of Nicaragua. Hydroelectric power is not available in Sonzapote, thus the analysis focuses on wind and solar technologies. As a long-term perspective is essential for developing successful projects [11], the operation and maintenance costs of the different components of the system along the lifespan of the project are considered. The algorithm used to support the design process is an adaptation of the one proposed in ref. [21] in order to consider also operation and maintenance costs, not only the initial investment: a sensitivity analysis is also carried out to illustrate the influence of these costs on the solutions obtained. The design hereby presented is the first detailed study of an off-grid electrification project with wind and solar energies at a micro-scale scale in Nicaragua. Furthermore, other features differentiate this study from previous ones encountered in literature: generators can be located in any point of the area without any restriction, not only close to demand points [18, 22] or in a limited number of pre-selected points [16] and the size of the analyzed community (88 users) is bigger than typical projects studied in literature [18, 22]. It aims to be a pilot project in order to facilitate governmental investments on renewable energy and spread their utilization in rural electrification projects in Nicaragua.

The paper describes the complete design process that is carried out following the steps next summarized. Firstly the analysis of the location, energy and power demands of all users of the community is carried out (Section 2). A detailed resource assessment is then developed by means of historical data, in-situ wind measurements and a specific micro-scale wind flow model (Section 3). The main components of an off-grid electrification project and the algorithm utilized to support the design defining generation (number, type and location of generators, controllers, batteries and inverters) and distribution (electric networks) systems considering real micro-scale wind resource variations are described (Section 4). The analysis of the design of the project in Sonzapote is then presented (Section 5). After defining most relevant techno-economic data (sub-Section 5.1), a sensitivity analysis is carried out considering different operation and maintenance costs' scenarios (sub-Section 5.2). The design configuration obtained considering an intermediate value of those costs is finally described in detail (sub-Section 5.3). Section 6 deals with conclusions.

2. Community description and demand assessment

Nicaragua is a country of Central America covering an area between longitude 83-88º W and latitude 11-14.5º N. Nicaraguan west and east borders are respectively the Pacific Ocean and the Caribbean Sea. The analyzed community is Sonzapote (municipality of Teustepe, province of Boaco) in the central highland of Nicaragua (Fig. 1). As shown in Fig. 1, in the area around the community the wind resource is highly variable due to the complex topography with sites with good or even excellent resource (mean wind speed of more than 7 m/s at 50 m a.g.l. - above ground level). The closest connection to the national electric grid is located at a distance of more the 3 km in hardly accessible terrain.

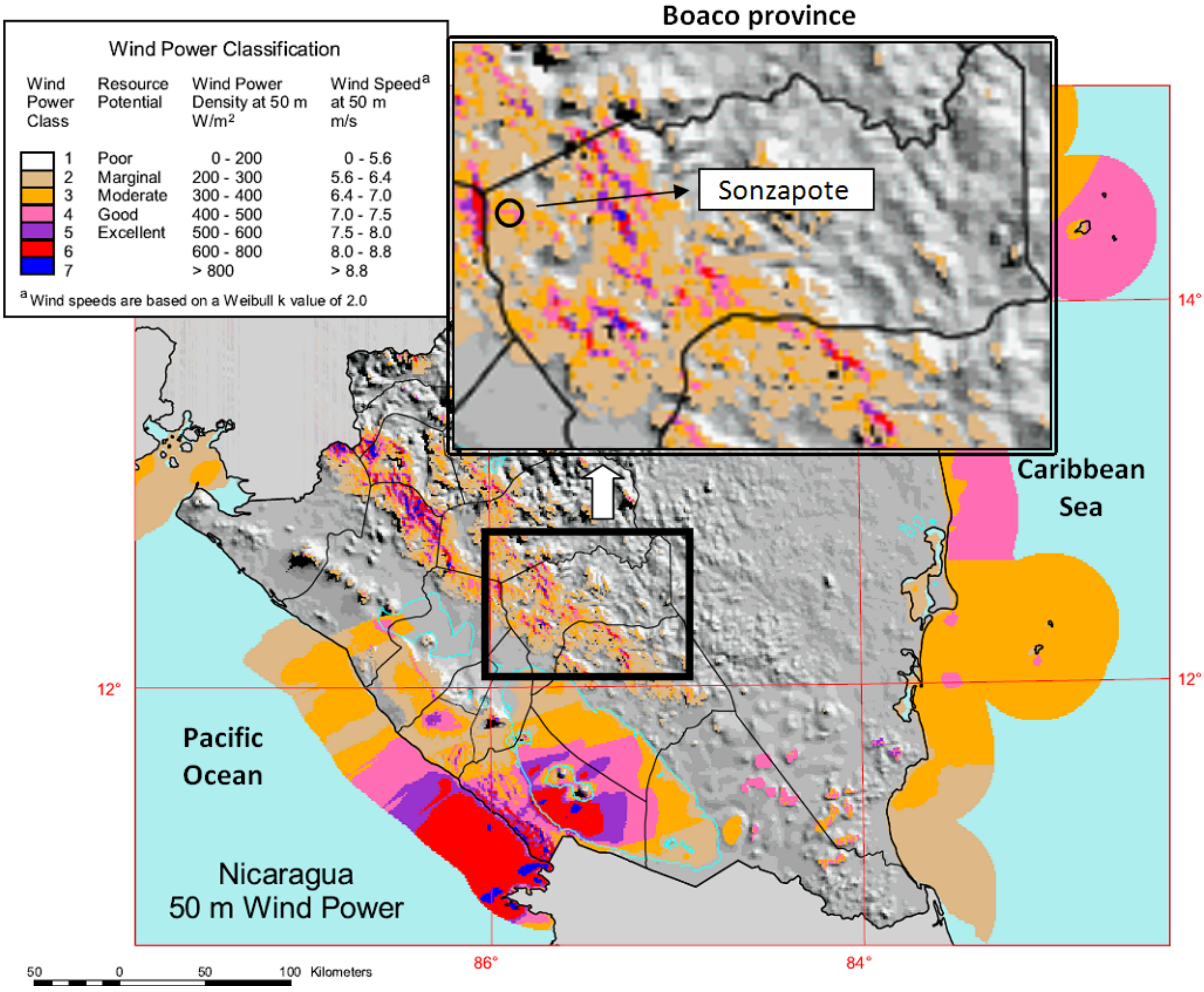

Fig. 1. Nicaragua topographical map with mean wind speed at 50 m a.g.l. [23].

Sonzapote is located at around 400-500 m above sea level (Fig. 2, see legend in the bottom right). The community is composed by 83 houses, 4 mini-markets, 1 school and 1 church with a total population of around 345 inhabitants covering an area of 1 km^2 (Fig. 2). Main activities in the community are related to the primary sector, as most of the population is dedicated to agriculture (mainly beans culture) and to extensive animal farming (mainly cows). The mini-markets sell primary alimentation products. The school is excluded from this study as it has already an electric supply for its consumption provided by solar panels.

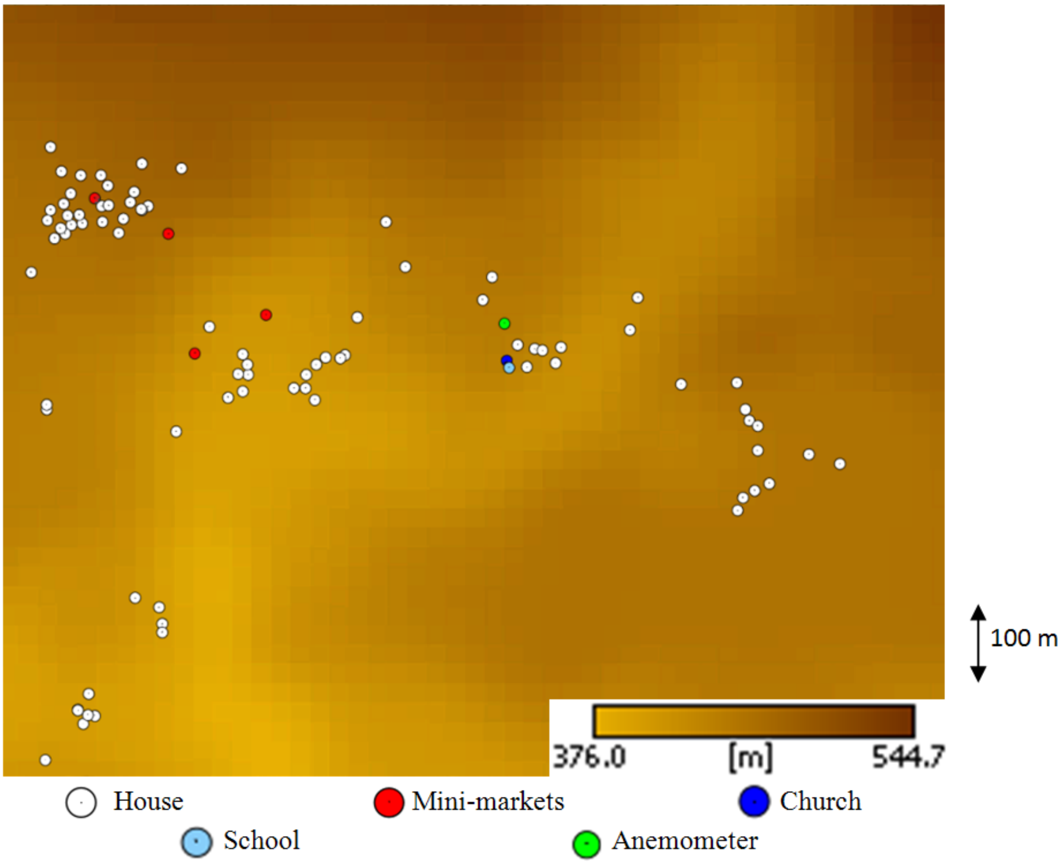

Fig. 2. Users locations in Sonzapote.

The electrical energy and power demands of the different users were estimated by the promoter of Sonzapote project (the Non-Governmental Organization Asofenix) according to recently implemented electrification projects in the region. Houses demand values in Table 1 correspond to 1 inhabitant per house; for houses with multiple inhabitants, increasing factors of +45 Wh/person·day and +15 W/person are applied respectively for energy and power demands.

Table 1 – Energy and power demand of the houses, the markets and the church in Sonzapote

Type of user	*Number of points*	*Energy demand [Wh/day]*	*Power demand [W]*
Houses	83	240	195
Markets	4	3975	660
Church	1	1500	900

3. Wind and solar resource assessment

In this Section, the solar (sub-Section 3.1) and wind (sub-Section 3.2) resource assessments in the community of Sonzapote are described. As the wind resource is much more variable than the solar one [3, 12], a detailed wind resource assessment is carried out including in-situ measurements and wind flow modelling.

3.1. Solar resource assessment

According to NASA database [24], in the region of Sonzapote the solar resource is pretty high with a mean global irradiance varying between 4.7 and 6.2 kWh/(m^2·day) along the year. In order to carry out a conservative analysis, the lowest resource month, i.e. November with 4.7 kWh/(m^2·day), is considered in this study. As spatial variation of global irradiance is lower than 5% in areas of less than 30x30 km even in mountainous areas [25], the accuracy of NASA climate database, with a resolution of around 50 km, is sufficient for the purpose of this study .

3.2. Wind resource assessment

The National Wind atlas of Nicaragua [23] shown in Fig. 1 gives information about mean wind speed and power density at 50 m a.g.l. with a grid spacing of 0.05º of latitude/longitude (around 5.5 km). In the central Sierra of Nicaragua the wind resource is highly variable with some sites having moderate to excellent wind resource. In specific, according to these data, the municipality of Teustepe is one of the few in which wind technology could be more favourable than the solar one [3]. However, due to the complex topography of the area of Sonzapote, data from the National atlas could be not directly utilized to evaluate the wind resource at a community scale. Therefore, a specific wind resource assessment study is needed [3].

Available historical wind climate data around Sonzapote are firstly analyzed (sub-Section 3.2.1) in order to identify the least resource season. Then the in-situ wind measurement campaign is described (sub-Section 3.2.2). As high wind resource spatial variability is expected in hilly terrain even at community level [12], a wind flow model is applied in order to extrapolate wind measurements to the whole area and evaluate micro-scale wind resource variations (sub-Section 3.2.3).

3.2.1 Historical wind data and global databases

The wind climate of the country is the typical of sub-tropical region with trade winds prevailing and dominant wind direction from east - northeast all along the year [24]. In Fig. 3 wind speed data from different sources are shown:

- Meteorological stations wind data: wind data at 10 m a.g.l. from the 2 meteorological stations closest to Sonzapote (MET1 and MET2). MET1 is located in the city of Muy-Muy (40 km north-east of Sonzapote) and data are available from 1974 to 2011. MET2 is located in the city of Juigalpa (69 km south-east of Sonzapote). In this case, wind data are available from 1982 to 2010.
- NASA Database: Wind data at 10 m a.g.l. of the NASA Database (with a resolution of 50 km) at Sonzapote location. The NASA database reports the ten-year annual average map obtained by a numerical re-analysis treatment of historical data [24].

All wind data analyzed show the same pattern, with higher winds from December to April and lower winds from May to October, with a local maximum in July and a global minimum in September.

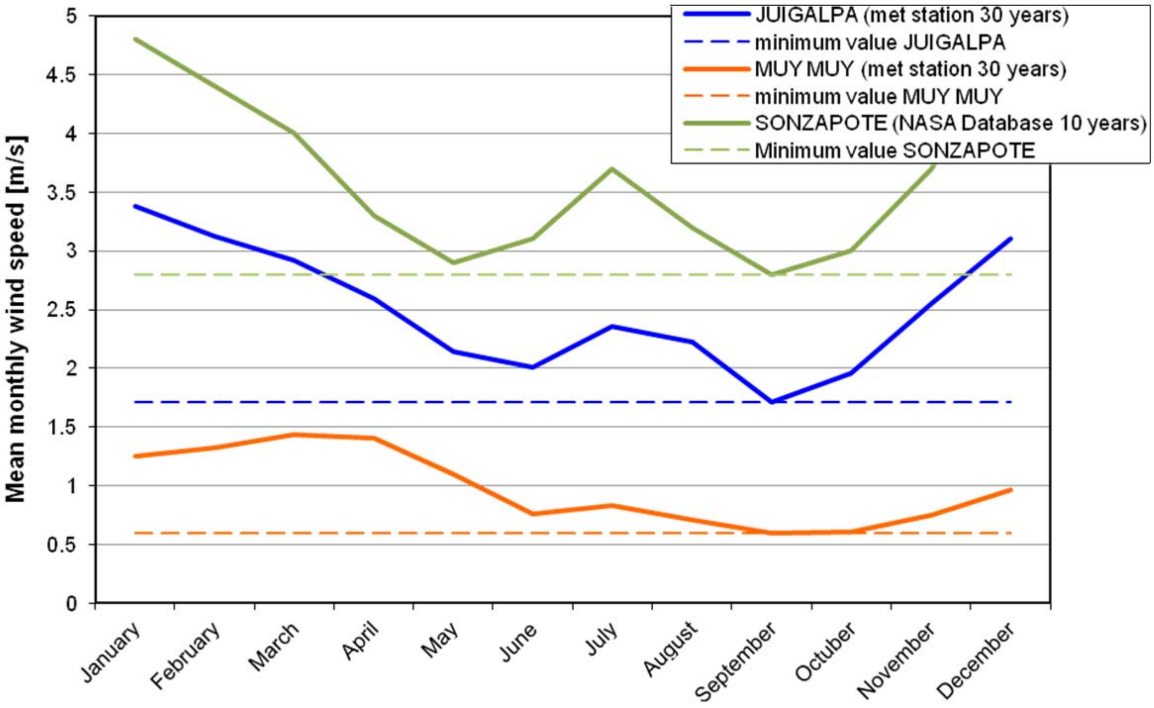

Fig. 3. NASA database wind data in Sonzapote and wind data of closest meteorological stations

3.2.2 In-situ wind measurements

According to the analysis of historical data, the measurement campaign was carried out during the minimum resource month, i.e. September.

An anemometer (Davis Instrument – Standard three-cup anemometer with wind vane) was installed in the centre of the community at a height of 8.5 m a.g.l. (Fig. 2), in an open-area close to the top of a small hill without surrounding obstacles. Wind speed and direction data were measured every second and mean value every 10 minutes were then registered by the instrument. Data were measured from the 22th of August till the 2nd of October, however only data from the 1st till the 30th of September are considered. Daily wind speed profile and wind rose are shown in Fig. 4.

The wind rose confirms the prevalence of trade winds with dominant wind direction from the northeast. Mean wind speed is 4.5 m/s with high diurnal variability: higher wind speeds are present during the day (6 m/s) while lower wind speeds during the night (3-3.5 m/s).

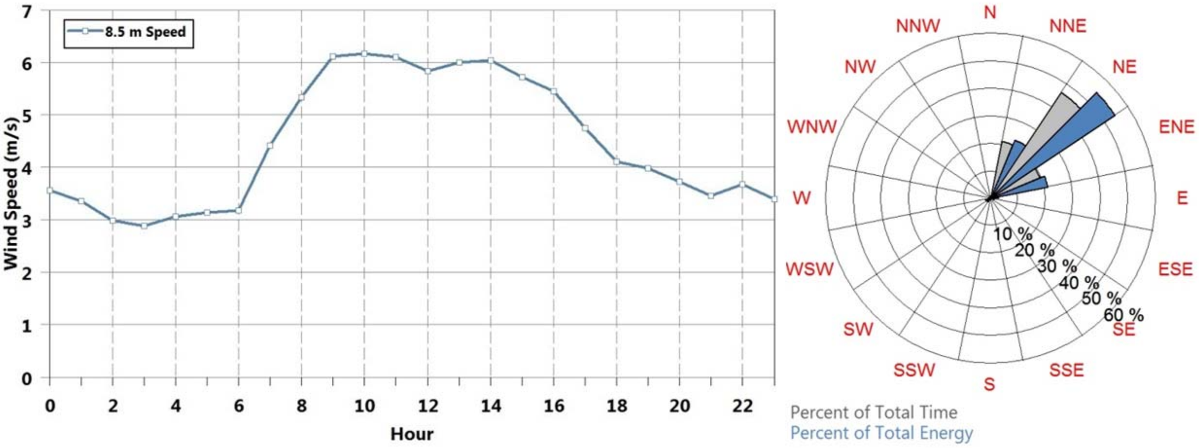

Fig. 4. Daily variation of the wind speed (left) and the wind rose (right) as by anemometer data

3.2.3 Micro-scale wind resource study

In order to evaluate the wind resource in the whole area of Sonzapote community a micro-scale analysis is carried out with specialized software, WAsP 9 [26]. WAsP is a wind flow model, which assumes that the slope of the surface is small enough to neglect flow separation and linearize flow equations. It permits extrapolating (horizontally and vertically) wind atlas data to every point of a certain area considering topography and roughness changes. WAsP software has been and is currently widely used for evaluating wind resource differences at a small scale (in areas of less than 10x10 km^2) and its operational limits are well known [27]. An important parameter to ensure WAsP performance is the topographical map quality. The available topographical map has a height contour interval of 10 m. According to WAsP literature [28, 12], the utilized map extended to more than 10 km in the prevailing wind direction (NE) and height contour lines were interpolated in order to reach an interval of 2 m in the area around the community. A roughness length of 0.2 m is given to most land areas, as terrain is composed by many low height trees, while a forest located in the center of the community is modeled with a higher roughness of 0.8 m [26].

Regarding the orographic context, a central parameter for defining the operational limits of the model is the ruggedness index (RIX) that indicates the fraction of the surrounding land above a critical slope (default 17°) [27]. It was verified that, with good input data and involved distance of few kilometres, WAsP estimation error is limited for rural communities' studies in medium complex terrain, i.e. RIX values around 10% in most of the area [12]. In Sonzapote community most of the area has RIX values below 10% (Fig. 5), therefore WAsP modelling is expected to be reliable.

Resulting wind resource map (Fig. 6) shows a high variability of resource in the analyzed area. Users are located in areas with a medium wind resource with mean wind speeds ranging from 2.5 m/s (in the forest area) to 5 m/s (at houses located at a higher elevation) at 10 m a.g.l. Meanwhile, a smooth hill located in the south of the community (the red area in Fig. 6) presents the highest wind resource with mean wind speeds up to 8 m/s. A recent study of the potential market for small wind turbines in Nicaragua [3] defines the break-even point between wind and solar technologies to be between 6 and 6.5 m/s (mean wind speed at 10 m a.g.l.). Therefore in this case it is not evident a-priori which technology results to be the most convenient and a detailed analysis is required. Furthermore, due to the high wind resource spatial variation, the utilization of both wind and solar technologies depending on the location could be the appropriate configuration.

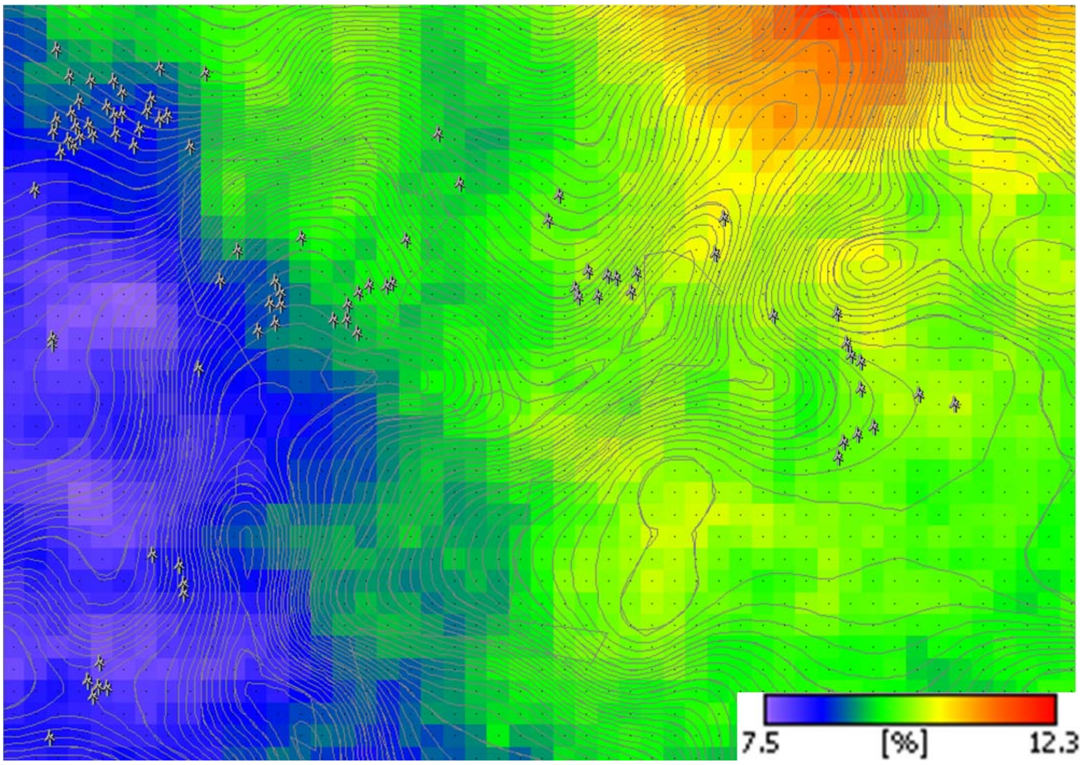

Fig. 5. Ruggedness Index (RIX) in Sonzapote.

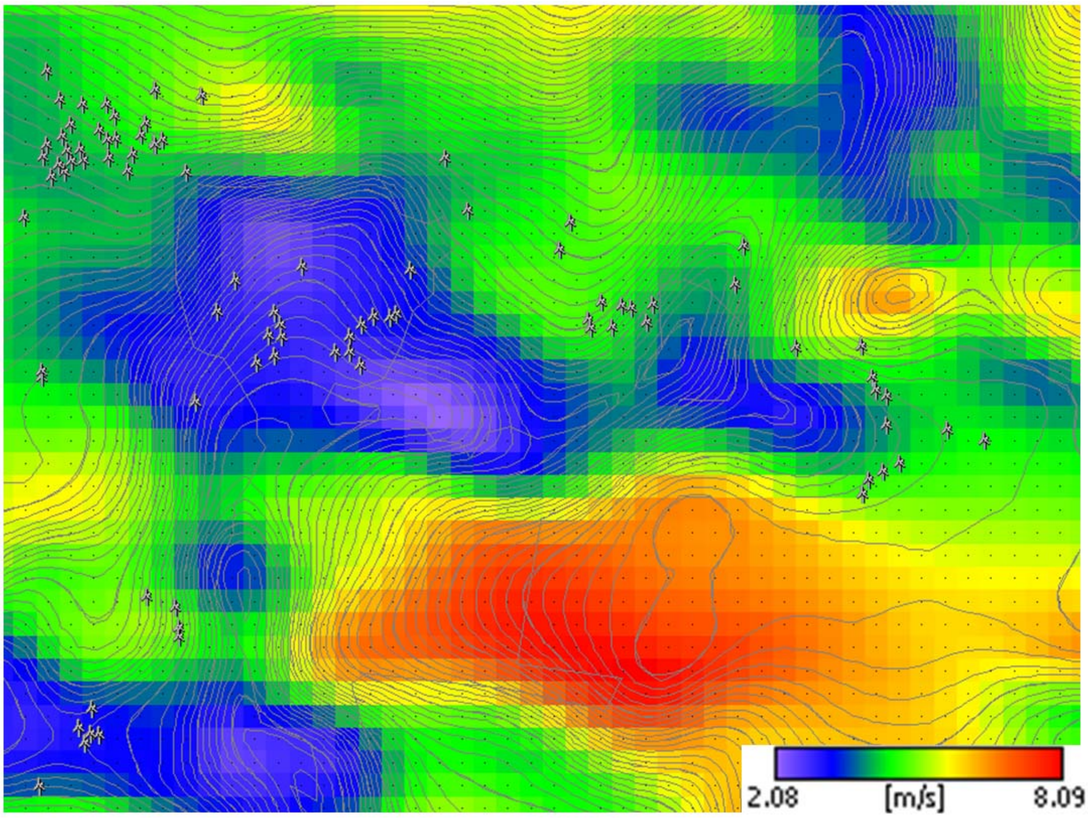

Fig. 6 Wind resource map showing mean wind speed at 10 m a.g.l. in Sonzapote area (1.2 x 1.2 km^2). The map has a grid spacing of 25m thus a total of 2450 grid points.

4. Off-grid electrification projects design

In this Section the components of a stand-alone electrification systems using wind-PV generation technologies are firstly described (sub-Section 4.1). Then the algorithm developed for supporting the design of the electrification project in Sonzapote is outlined (sub-Section 4.2).

4.1 Components of the system

The main components of a stand-alone rural electrification system based on wind and solar energies with microgrid distribution are shown in Fig. 7:
1) Wind turbines/solar panels: produce energy in alternating (wind turbines) or direct (solar panels) current.
2) Wind/solar controllers: convert to direct current (DC) and control the charge/discharge of the batteries.
3) Batteries: store the energy produced by the generators, receive and supply electricity at DC.
4) Inverters: convert direct to alternating current (AC) at the nominal voltage.
5) Low voltage cables: distributes the energy to the users.
6) Electric meters: measure the energy consumed at the demand points.
7) Users (or demand points): consume the energy, such as houses, markets, churches, etc.

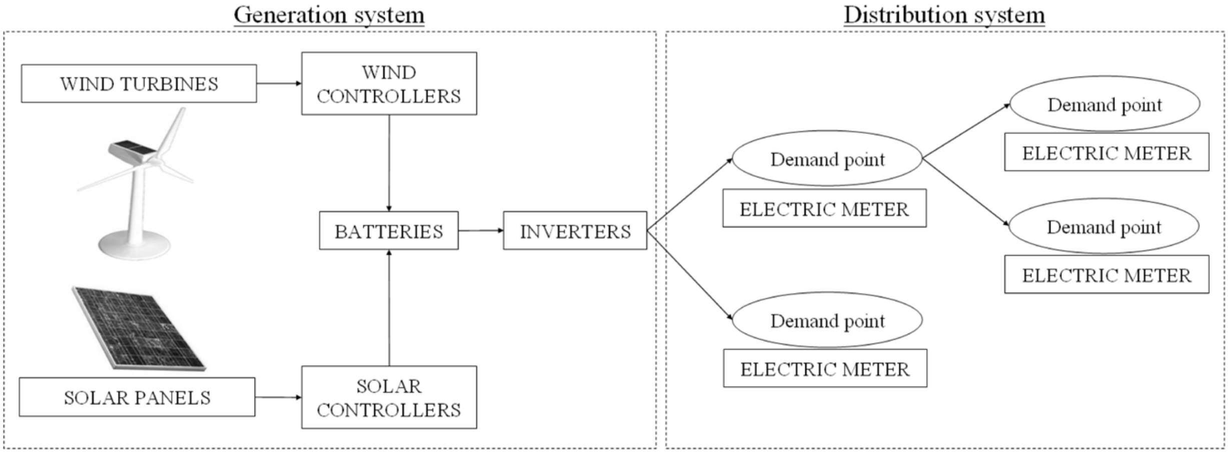

Fig.7. Main components of a hybrid wind-PV electrification system [20]

The generation system (or generation point) is composed by the generators (wind turbines and solar panels), controllers, batteries and inverters. The energy produced by a generation system is distributed to the users by electric cables (distribution system). If there are multiple users connected to the generation system they form a “micro-grid”, while if there is only one user connected with the generation system in its own location then we called it an “independent generation point”.

4.2 Design algorithm

The design of an hybrid off-grid electrification project using local available resources and a combination of independent generation points and microgrids is a hard combinatorial optimization problem, called AVEREMS (Autonomous Village Electrification through

Renewable Energy and Microgrid Systems) [20]. A solution to the AVEREMS problem refers to a design configuration defining generation points' locations and components number and type (generation system design) and microgrids structure (distribution system design) [20]. The aim is to find the lowest cost solution that accomplish with the energy and power demands of each user, taking into account energy resource maps and different technical constraints.

Recently a heuristic algorithm was presented in order to solve the AVEREMS design problem considering wind and solar energies [20, 21]. The objective function, the constraints of the problem and the complete description of the solving algorithm can be found in ref. [21]. Next, these are briefly resumed:

- Objective function: To minimize the initial investment cost of the project considering all the components defined in Fig. 7, i.e. wind turbines, wind controllers, PV panels, solar controllers, batteries, inverters, meters, and cables.

- Constraints:
    - *Generation system*: At each generation point, generators, controllers, inverters and batteries must be installed in order to cover microgrid total energy and power demands. Generators and batteries must satisfy the energy demand, while inverters must fulfil the power demand. For the dimensioning of the generators, batteries and inverters the following aspects must be also considered: resource available in the area, energy and power losses due to components' efficiencies, the minimum days of autonomy and the maximum battery discharge factor. Controllers are dimensioned depending directly on the installed generators.
    - *Distribution system*: Every demand point of a microgrid must be connected to the generation system by an electric cable. The type of cable installed must satisfy maximum permitted voltage drop considering nominal distribution voltage, and cable resistance and maximum intensity. Microgrid structure is radial. Electric (consumption) meters are generally installed in microgrid points to measure their consumption [22].

- Solving algorithm: The procedure consists of a multi-start algorithm, based on the Greedy Randomized Adaptive Search Procedure [29]. In each iteration a solution is obtained following a 2-phases procedure consisting of a randomized solution construction phase and then an improvement phase (of the solution obtained by the construction phase) which is subsequently repeated till no further enhancement is achieved. The best solution obtained by all the iterations is finally returned. This heuristic procedure was verified to highly improve solutions obtained by the exact model [22] for communities with more than 40 demand points [20].

For the design of the electrification project in Sonzapote, a long-term investment perspective is highly recommended as operation and maintenance costs could be critical in Nicaragua [11, 3]. In this sense, the Total Life-Cycle Cost (*TLCC*) and the Levelized Cost of Energy (*LCOE*) are common indicators when comparing different design alternatives from a project lifetime perspective [30, 31, 15, 32]. For this reason, the algorithm previously described was adapted in order to consider the total life-cycle cost of the project, not only the initial investment cost [20, 21], as the objective function.

Given I the initial investment cost [\$], $O\&M_n$ the total operation and maintenance cost in the year n [\$], d the nominal discount rate [%] and N the project lifetime [years], the $TLCC$ [\$] of each component (Fig. 7) is calculated as [30]:

$$TLCC = I + \sum_{n=1}^{N} \frac{O\&M_n}{(1+d)^n} \quad (4.1)$$

Once a design configuration is obtained, the $LCOE$ [\$/kWh] of the project can be calculated as a function of the $TLCC$, the annual generated energy [kWh] (E) and a uniform capital recovery factor (depending on the nominal discount rate and the project lifetime) [30]:

$$LCOE = \frac{TLCC}{E} \cdot \frac{d(1+d)^N}{(1+d)^N - 1} \quad (4.2)$$

This modified version of the algorithm presented in ref. [20, 21], i.e. considering the $TLCC$ of the project as the objective function, is used to properly support the design of Sonzapote project (Section 5); from now on it will be referred to as the “design algorithm”.

Besides including operation and maintenance costs in the design, it should be noted that this is the first study in which generators can be located in any point of the area without any restriction, not only close to demand points [18, 22] or in a limited number of pre-selected points [16]. In fact, a total of 2533 points, i.e. the 88 demand points plus all grid points of the wind resource map of the community (Fig. 6), are considered as possible generation points by the design algorithm. In this case, the a-priori selection of generation would be effectively highly difficult due to the complex resource and demand distributions in Sonzapote (Fig. 5 and Fig. 6). The application of the design algorithm permits obtaining an appropriate design configuration that takes advantage of the best resource areas, which, as results from the wind resource assessment (Fig. 6), are highly dispersed and located far from the users.

5. Sonzapote project design proposal

In this Section the design of Sonzapote electrification project is analyzed. In sub-Section 5.1 the main input data and hypothesis for the design analysis are defined, then in sub-Section 5.2 multiple design options considering different operation and maintenance (O&M) costs’ scenarios are evaluated with the support of the design algorithm (sub-Section 4.2). Finally in sub-Section 5.3 the design configuration obtained with intermediate value of O&M costs is described in detail.

5.1 Techno-economic data

Input data required for the design of off-grid electrification projects can be divided into three types: demand, resource and techno-economic data. The characteristics resulting from the demand (users’ position, electrical energy and power demand) and resource (wind and solar resources in the area) evaluations were already defined in Sections 2 and 3.

The techno-economic characteristics hereby described refer to the definition of the technical and economical data of all the available components of the electrification project (Fig. 7). As stated, the total life-cycle cost ($TLCC$) of each component is calculated by the design algorithm according to equation (4.1) given the initial investments and O&M costs. The definition of the initial investment and O&M costs of the various components (wind turbines, solar panels, controllers, batteries, inverters, cables and meters) considered in the design of Sonzapote electrification project are reported in sub-Sections 5.1.1 and 5.1.2.

5.1.1 Initial investment costs

A recent study of the market for small wind turbines in Nicaragua analyses in detail the initial investment costs of wind turbines, solar panels, batteries and inverters for off-grid electrification projects [3]. Therefore, most of components' data were taken from that study. This information was expanded including a more complete range of components with data provided by manufacturers and local NGOs, following the same cost assumptions as in [3]. All wind turbines considered are commercial ones with a minimum warranty of 5 years and a verified power curve. The costs and the characteristics of the components considered are shown in Table 2. It should be clarified that the initial investment also includes:

- Installation cost of the generation system (included in wind turbines and solar panels costs).
- Administration costs (30%) and VAT (15%)
- Import duty (10%) and transportation costs (6-10%) for imported components.

Table 2 – Characteristics and initial investments of the different components considered in this study

Wind turbines[a]	Nominal power [w] / Tower height [m]	Initial investment [$]	Comments
Type 1	200 / 15	2273	For wind resource in the area see Fig. 6. Turbines power curves are supplied by the manufacturer.
Type 2	1050 / 18	11216	
Type 3	2400 / 18	17861	
Type 4	3500 / 18	25494	
Type 5	7500 / 20	67140	
Solar panels	Nominal power [W]	Initial investment [$]	Comments
Type 1	55	329	Solar resource: 4.7 kWh / m^2·day (see sub-Section 3.1)
Type 2	250	916	
Type 3	2500	9158	
Solar controllers	Maximum power [W]	Initial investment [$]	
Type 1	72	65	
Type 2	540	507	
Type 3	5400	5070	
Batteries	Capacity [Wh]	Initial investment [$]	Comments
Type 1	1290	141	Efficiency: 0.85
Type 2	2520	300	Maximum discharge rate: 0.6
Type 3	25200	3000	Days of autonomy: 2
Inverters	Maximum power [W]	Initial investment [$]	Comments
Type 1	400	65	Efficiency: 0.85
Type 2	1500	312	
Type 3	5000	1040	
Cables[b]	Maximum intensity [A] / Resistivity [Ω/km]	Initial investment [$/m]	Comments
Triplex 6	70 / 2.416	3.4	Nominal voltage: 120 V Maximum voltage: 128.4V Minimum voltage: 111.6V
Triplex 4	100 / 1.4	3.9	
Triplex 2	150 / 0.964	4.5	
Triplex 1/0	205 / 0.604	5.4	
	Initial investment [$]	Comments	
Electric meters	50	Installed only in users of a microgrid	
Generation system house	600	Installed only in the generation system of a microgrid	

[a] Wind turbines cost includes wind controllers

[b] Cables' cost includes 25 feet height electric posts

Community training and capacity building are a fundamental issue that should be always carried out when implementing this kind of projects [33, 3, 34]. However, as these activities require a fix cost that must be added to each of the compared design options, their cost is not considered in this study.

5.1.2 Operation and maintenance costs

The O&M costs are a critical issue for the success of rural electrification projects [11, 35]. However these costs are not easy to establish for wind and solar energies as, beside community remoteness, they depend on external factors hardly assessable a-priori, such as the availability of trained maintenance providers, community dynamics and the ability to train local users [35]. For this reason, in some cases only initial investment costs are considered, as they are sometimes the most critical limitation to the implementation of renewable energy projects [36]. When included, annual O&M costs of the various components are generally assumed to be a percentage with respect to the initial investment cost. Analyzing recent studies on the design of off-grid electrification projects in developing countries [31, 32, 37, 38, 39, 40, 41, 42], different values were encountered regarding wind turbines and solar panels annual O&M costs: for solar panels they vary from 0.1% till 2%, while for wind turbines vary from 1% till 3.5% of the initial investment cost.

Due to this significant variability in encountered values, in this study we carry out a sensitivity analysis taking into account different O&M costs scenarios in order to analyze how these can affect the selection of the most appropriate technology. As wind turbines have dynamic parts that are more susceptible of breakdowns, their O&M costs are considered the double of solar panels O&M costs in all scenarios, a common assumption according to [31] . The following scenarios are considered (Table 3):

- Scenario 0: no O&M costs, i.e. taking into account only initial investment costs, as done in ref. [36, 16].
- Scenario 1: Low O&M costs: 0.5% for solar panels and 1% for wind turbines
- Scenario 2: Intermediate O&M costs: 1.25% for solar panels and 2.5% for wind turbines
- Scenario 3: High O&M costs: 2% for solar panels and 4% for wind turbines

Table 3 –Different O&M costs scenarios

	Annual O&M [% of initial investment]			
	Scenario 0[a]	*Scenario 1*	*Scenario 2*	*Scenario 3*
Solar panels	0%	0.5%	1.25%	2%
Wind turbines	0%	1%	2.5%	4%

[a] no O&M costs neither replacement are considered in Scenario 0

Besides O&M costs for solar panels and wind turbines, all other hypothesis and cost assumptions for *TLCC* and *LCOE* calculation (equations (4.1) and (4.2)) are the same for scenarios 1, 2 and 3 [31, 32, 43]:

- nominal discount rate of 10% and project life time of 15 years;
- wind turbines and solar panels lifetime are considered longer than 15 years therefore no replacement is considered;
- annual O&M costs are 0,5% of the initial investment for controllers and inverters (replacement every 10 years) and 4% for batteries (replacement every 5 years);
- O&M costs are considered negligible for cables, electric meters and the micro-grid generation system house.

5.2 Sensitivity analysis of O&M costs scenarios

Hereby different configurations for the design of Sonzapote project are analyzed based on the O&M costs scenarios previously described. The design algorithm was launched with a maximum calculation time of 5 hours for each solution, a lapse of time considered affordable taking into account the problem to be solved.

For each O&M scenario described (Table 3), two design configurations are compared in Table 4:

4) Independent configuration: Independent generation systems are installed at each demand point (thus no microgrids' construction is considered). This is the configuration generally applied when electrifying isolated communities through autonomous systems using renewable energies [14, 15].
5) Microgrids configuration: Design configuration obtained by the design algorithm combining independent systems and microgrids.

Due to the medium – low wind resource at demand points, independent configurations are always based on solar energy: solar panels are installed at each demand point in order to cover their demand. When considering microgrids (microgrids configuration), wind energy production could become relevant, as bigger turbines could be installed in the best resource areas. The O&M cost scenario considered highly affects wind energy production (Fig. 8): as low the O&M costs of wind turbines and solar panels, higher is the share of wind energy over the total production that varies from almost 60% in Scenarios 0 and 1 (no or low O&M costs) to 0% in Scenario 3 (high O&M costs). Effectively best wind resource area in Sonzapote has a mean wind speed between 7 and 8 m/s, really close to the break-even point between commercial wind and solar technologies for off-grid generation that is above 6.5 m/s in Nicaragua [3].

Regarding the costs, the solutions obtained by the design algorithm (microgrid configuration) highly reduce project costs in comparison with the independent configuration (see last raw of Table 4). The decrease in cost is related with the percentage of energy produced by wind energy: as higher the amount of energy produced by wind turbines higher is the improvement in comparison with the independent configuration (Fig. 8). This is due to the bigger effect of the economies of scale on wind energy in comparison with solar energy. However, even when only solar energy is used (Scenario 3), solution with microgrids improves independent configuration of around 16%.

Table 4 – Independent and microgrid configurations obtained with different O&M costs scenarios

		Scenario 0	*Scenario 1*	*Scenario 2*	*Scenario 3*
Independent configuration	Cost [$][a]	152377	210010	215346.4	220706.5
	% of wind energy	0%	0%	0%	0%
	% of solar energy	100%	100%	100%	100%
Microgrids configuration	Cost [$][a]	126416	174169	180131	185362
	% of wind energy	59%	57%	31%	0%
	% of solar energy	41%	43%	69%	100%
	Cost decrease with respect to independent configuration	17.0%	17.1%	16.4%	16.0%

[a] Solution cost refers to initial investment for Scenario 0 and to total life-cycle cost for scenarios 1, 2 and 3.

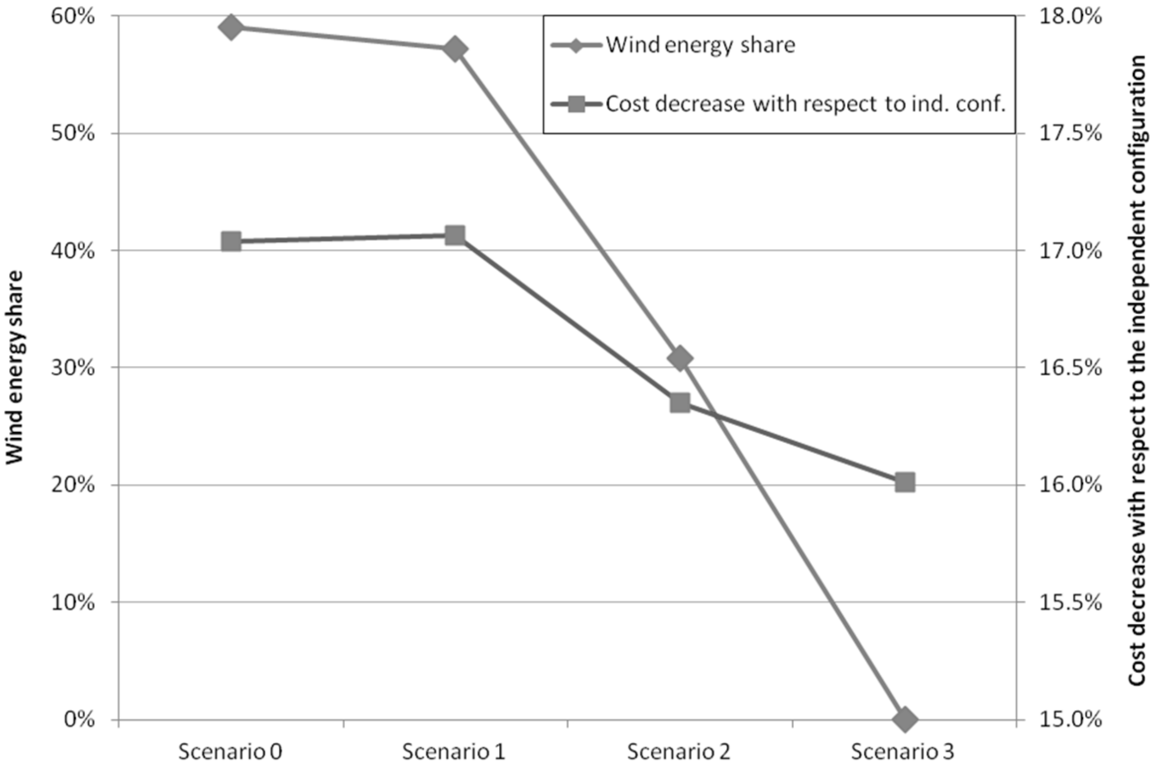

Fig. 8. Wind energy share (% of the total produced energy) and cost decrease (%) of the microgrids configuration in comparison to the independent configuration obtained with the different analyzed O&M costs scenarios.

5.3 Intermediate O&M costs configuration

As previously stated, the real O&M costs are a key issue for the success and sustainability of a rural electrification project [35] [United Nations, 2014]. For this reason, various O&M scenarios were analyzed in sub-Section 5.2. In all cases, the microgrids configuration considerably improves the independent configuration. The final selection of the most adequate design configuration will be done by project promoter after carrying out a detailed study of local providers and analyzing community feedback from the training.

As an example, hereby we describe in detail the microgrids configuration obtained with intermediate O&M costs (Scenario 2) that a-priori seems to be the most appropriate for Sonzapote: Scenario 1 is highly optimistic while Scenario 3 is probably too conservative as the community is located not too far from supply/maintenance centres, i.e. 90 minutes by car to the capital city Managua, and few community inhabitants are already trained to do small maintenance operations, as solar panels are already installed in the school.

The intermediate cost configuration, i.e. the microgrids configuration obtained considering intermediate O&M costs (1.25% for solar and 2.5% for wind energy), is composed by 3 microgrids and 4 independent generation points (Fig. 9):

- Microgrid 1 is based on wind energy: a wind turbine of 2.4 kW is installed in the top of the hill located in the south-east of Sonzapote with a mean wind speed around 8 m/s. The microgrid connects 3 groups of highly concentrated users (34 users in total) located in the east, centre and south-west of the community.

- Microgrids 2 and 3 are based on solar energy with nominal powers of 4.3 kW and 5 kW and connecting 22 and 28 users respectively. Generation points of both microgrids are located in users with maximum demand, i.e. mini-markets (see Fig.2).
- The 4 independent generation points (orange points) are users not connected to any microgrid having their own solar panels: P1 is an isolated house, while P2 and P3 are mini-markets that have their own generators in order to minimize energy losses. The connection of any of these points to microgrids 2 or 3 would increase project cost. Even if P0 is really close to the microgrid 3, it is slightly cheaper (around 100 $) to electrify P0 as an independent generation point than to connect it to the microgrid. However, when implementing the project, the promoter of the project may connect P0 to microgrid 3 for practical and management reasons.

This configuration reduces the total life-cycle cost of the project of 16.4% in comparison with the independent configurations; the levelized cost of energy (*LCOE*) is 0.838 $/kWh, 14% lower than the 0.975 $/kWh of the independent configuration. The intermediate cost configuration therefore combines independent systems, solar based microgrids and wind microgrids in order to connect concentrated groups of users, to take advantage of best wind resource areas (in this case located far from demand points) and thus reducing the *LCOE* of the project.

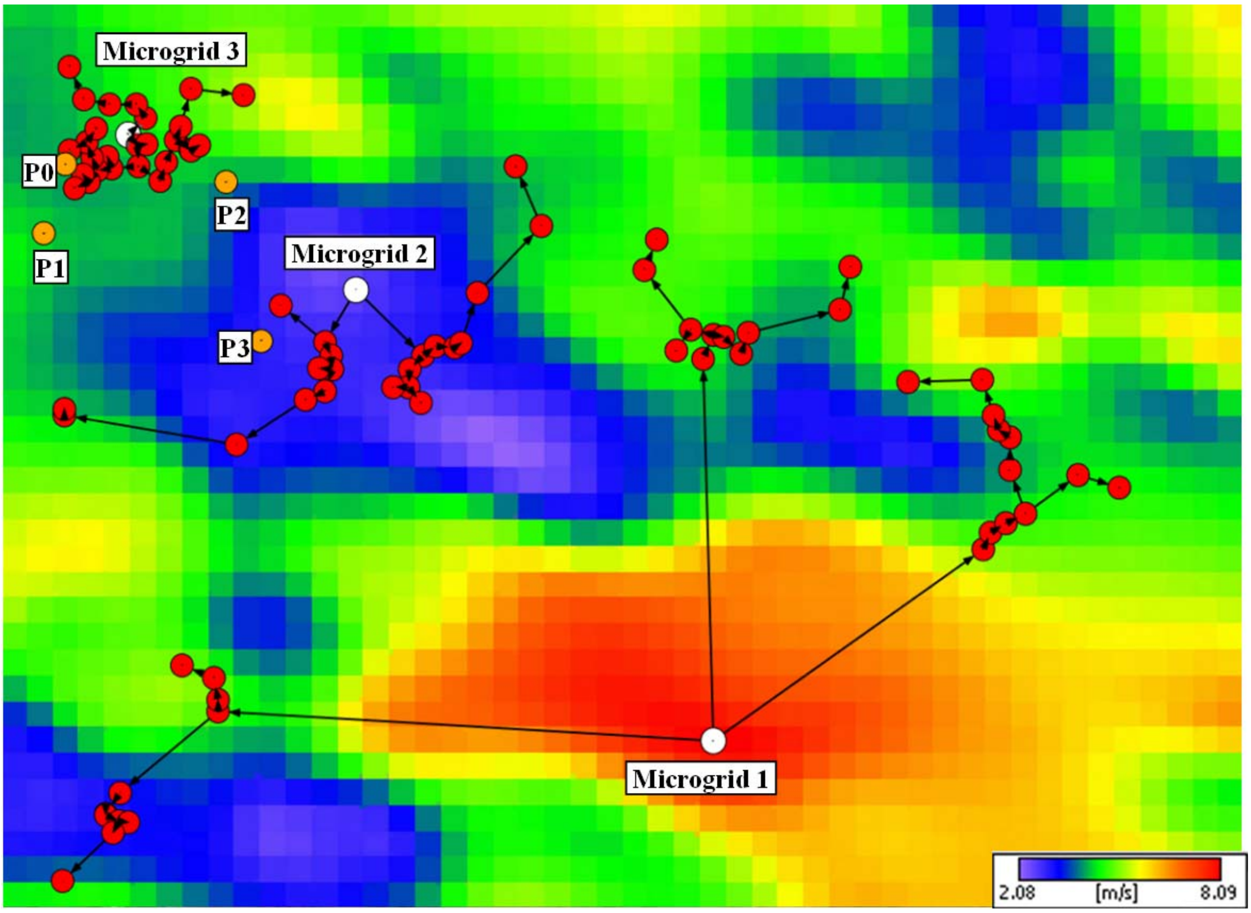

Fig. 9. The intermediate costs configuration (Scenario 2). White points are microgrid generation points, red points are the points connected to a microgrid, orange points are independent generation points.

6. Conclusions

In this study, the design of the off-grid electrification project based on hybrid wind-PV energies in a rural community (Sonzapote) is analyzed. Sonzapote is a community located in the central highlands of Nicaragua composed by 88 users with a population of around 350 inhabitants.

Firstly the wind resource assessment is realized analyzing wind resource variation at a micro-scale. While solar resource is considered uniform, the detailed wind resource assessment shows high wind variability in all the communities, with low resource within them, but greater resource in areas some hundred meters far. Secondly, a recently developed algorithm for the design of rural electrification projects combining microgrids and individual generators is adapted in order to consider the total life-cycle cost, including also the operation and maintenance (O&M) cost, instead of only the initial investment cost. This adapted design algorithm is then applied in order to obtain various design configurations. The analysis of different costs scenarios showed that as lower the O&M costs of wind turbines and solar panels, higher is the share of wind energy over the total production. In all scenarios, the configuration that considers both individual systems and microgrids (the microgrids configuration obtained utilizing the described design algorithm) significantly improves the configuration with only individual systems (the independent configuration).

The microgrids configuration considering intermediate O&M costs is finally described in detail. It combines independent systems, solar based microgrids and wind based microgrids in order to connect concentrated groups of users taking advantage of best wind resource areas. This configuration reduces the total life-cycle cost of the project and the levelized cost of energy of 16.4% and 14% respectively in comparison with the independent configuration.

This design study presents some novelty features in comparison with previous literature: generators can be located in any point of the area without any restriction, thus permitting taking into account real micro-scale resource variations and identifying best resource areas. Furthermore, the size of the studied community (88 users) is bigger than typical projects previously analyzed. Finally, the design hereby presented is the first detailed renewable energy study for off-grid generation project at a community scale in Nicaragua. It aims to be a pilot project in order to facilitate governmental investments on renewable energies and spread their utilization in rural electrification projects in Nicaragua.

Acknowledgments

This paper was supported by the Spanish Ministry of Education (FPU grant AP2009-0738), the MICINN project ENE2010-15509 and co-financed by the Centre for Development Cooperation of the Universitat Politècnica de Catalunya. M.R. is very grateful for all the assistance and support provided by people of the AsoFenix office in Managua, to Philipp Blechinger and Jon Leary for the consultancy on the economic study, to Joaquin Mataix, Roberto Clemente and Alexi Funez for the data about wind turbines characteristics and costs.

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