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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 (CEPAL, 2013). 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 (Marandin et al., 2013; PRONicaragua, 2012). 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% (PRONicaragua, 2012). On the other side, the social and economical advantages of providing electricity to rural communities in Nicaragua have been clearly demonstrated (Apergis and Payne, 2011; Grogan and Sadanand, 2013), such as the improvement in sanitations facilities, the increase in educational services quality and the development of local business and women employment. Despite various institutional efforts (Hansen, 2006), about 22% of the total Nicaraguan population and 40% of the rural population still do not have access to electricity (CEPAL, 2013; Marandin et al., 2013).

In the past, most of the efforts in relation to Nicaragua's rural electrification were focused on grid extension (Hansen, 2006). 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 (Grogan and Sadanand, 2013). 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 (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 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 (Domenech et al., 2014; Nandi and Ghosh, 2010). 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 (Wang, 2011) of the National Sustainable Electrification and Renewable Energy Program (Inter-American Development Bank, 2012), 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 (Marandin et al., 2013). As known, wind resource is highly variable and detailed wind resource studies are required for the correct design of the system (Alliance for Rural Electrification, 2011; Domenech et al., 2014; Ranaboldo et al., 2014b). 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 (Marandin et al., 2013). Anyhow, hybrid systems that combine different resources are generally the most promising generation option (Alliance for Rural Electrification, 2011; Marandin et al., 2013; Neves et al., 2014) 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 (Alliance for Rural Electrification, 2011; Neves et al., 2014).

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 (Leary et al., 2012; Lemaire, 2011), 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 (Ranaboldo et al., 2014a), enhance the flexibility of the system and improve equity between user consumptions as all connected users share the same generated energy (Kirubi et al., 2009). In scattered communities with isolated users, the combination of independent generation systems and microgrids is generally the cheapest design configuration (Ferrer-Martí et al., 2011). 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 (Ranaboldo et al., 2014b). 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 (Ranaboldo et al., 2014a). 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 (Ranaboldo et al., 2014a).

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 (Luna-Rubio et al., 2012; Sinha and Chandel, 2014). In the past years, many software 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 (Sinha and Chandel, 2014). 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 (Ranaboldo et al., 2014c, 2014d).

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 (Alliance for Rural Electrification, 2011), the operation and maintenance costs of the different components of the system along the lifespan of the project are considered. The design process is supported on a novel optimization algorithm based on the one proposed in Ranaboldo et al. (2014d), 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 in Nicaragua (and one of the first ones in Central and South America) to combine wind and solar energies as well as microgrids and independent generation points according to micro-scale resource and demand analysis. 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 (Ferrer-Martí et al., 2013, 2011) or in a limited number of pre-selected points (Ranaboldo et al., 2014a) and the size of the analyzed community (88 users) is bigger than typical projects studied in literature (Ferrer-Martí et al., 2013, 2011). 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 (National Renewable Energy Laboratory, 2005), 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.

Please insert Figure 1

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.

Please insert Figure 2

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.

Please insert Table 1

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 (Marandin et al., 2013; Ranaboldo et al., 2014b), 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 (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. As spatial variation of global irradiance is lower than 5% in areas of less than 30x30 km even in mountainous areas (Gueymard and Wilcox, 2011), 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 (National Renewable Energy Laboratory, 2005) 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 (Marandin et al., 2013). 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 (Marandin et al., 2013).

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 (Ranaboldo et al., 2014b), 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 (NASA, 2011). 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 (NASA, 2011).

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.

Please insert Figure 3

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).

Please insert Figure 4

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 (Mortensen et al., 2007). 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 (Bowen et al., 2004). 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 (Mortensen, 2008; Ranaboldo et al., 2014b), 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 (Mortensen et al., 2007).

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). 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 (Ranaboldo et al., 2014b). 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 (Marandin et al., 2013) 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.

Please insert Figure 5

Please insert Figure 6

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.

<u>Please insert Figure 7</u>

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) (Ranaboldo et al., 2014c). 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) (Ranaboldo et al., 2014c). 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 (Ranaboldo et al., 2014c, 2014d). The objective function, the constraints of the problem and the complete description of the solving algorithm can be found in Ranaboldo et al. (2014d). 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 (Ferrer-Martí et al., 2013).

- Solving algorithm: The procedure consists of a multi-start algorithm, based on the Greedy Randomized Adaptive Search Procedure (Feo and Resende, 1995). 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 (Ferrer-Martí et al., 2013) for communities with more than 40 demand points (Ranaboldo et al., 2014c).

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 (Alliance for Rural Electrification, 2011; Marandin et al., 2013). 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 (Blechinger et al., 2014; ESMAP, 2007; Leary et al., 2012; Short et al., 1995). 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 (Ranaboldo et al., 2014c, 2014d), 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 (Short et al., 1995):

$$TLCC = I + \sum_{n=1}^{N} \frac{O\&M_n}{(1+d)^n} \quad (4.1)$$

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) (Short et al., 1995):

$$LCOE = \frac{TLCC}{E} \cdot \frac{d(1+d)^N}{(1+d)^N - 1} \quad (4.2)$$

This modified version of the algorithm presented in Ranaboldo et al. (2014c, 2014d), 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 (Ferrer-Martí et al., 2013, 2011) or in a limited number of pre-selected points (Ranaboldo et al., 2014a). 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 and results

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 next 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 (Marandin et al., 2013). 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 Marandin et al. (2013). 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.

Please insert Table 2

Community training and capacity building are a fundamental issue that should be always carried out when implementing this kind of projects (Marandin et al., 2013; Ortiz et al., 2012; Terrapon-Pfaff et al., 2014). 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 (Alliance for Rural Electrification, 2011; Schnitzer et al., 2014). 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 (Schnitzer et al., 2014). 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 (Akella et al., 2007). 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 (Aagreh and Al-Ghzawi, 2013; Bekele and Palm, 2010; Blechinger et al., 2014; Dorji et al., 2012; ESMAP, 2007; Kaabeche and Ibtiouen, 2014; Maleki and Askarzadeh, 2014; Nouni et al., 2007), 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 ESMAP (2007). 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 Akella et al. (2007) and Ranaboldo et al. (2014a).

- 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

Please insert Table 3

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 (Blechinger et al., 2014; ESMAP, 2007; Sumanik-Leary, 2013):

- 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:

1) 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 (Leary et al., 2012; Lemaire, 2011).
2) 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 (Marandin et al., 2013).

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%.

Please insert Table 4

Please insert Figure 8

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 (Schnitzer et al., 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, with a total cable length of 2231 m. As an energy backup, a bank of 61 batteries of 1290 Wh are installed.
- Microgrids 2 and 3 are based on solar energy with nominal powers of 4.3 kW and 5 kW and connecting 22 (total cable length of 864 m) and 28 users (total cable length of 521 m), respectively. Generation points of both microgrids are located in users with maximum demand, i.e. mini-markets (see Fig.2). Besides, 56 and 48 batteries of 1290 Wh are respectively installed in microgrids 2 and 3 to support the energy supply.
- The 4 independent generation points (orange points) are users not connected to any microgrid having their own solar panels: P0 is a house supplied by a solar panel of 250 W and 3 batteries of 1290 Wh; P1 is also a house supplied by 3 panels of 55 W and 2 batteries of 1290 Wh; and P2 and P3 are mini-markets each one supplied by 5 panels of 250 W, a panel of 55 W and 15 batteries of 1290 Wh. Connecting any of these points to microgrids 2 or 3 would increase project cost. Even for P0, which is really close to microgrid 3, the independent electrification is slightly cheaper (around 100 $) 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.

Please insert Figure 9

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 independent 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 independent systems and microgrids (the microgrids configuration obtained utilizing the described design algorithm) significantly improves the configuration with only independent 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

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Figure Captions

Fig. 1. Nicaragua topographical map with mean wind speed at 50 m a.g.l. (National Renewable Energy Laboratory, 2005).

Fig. 2. Users locations in Sonzapote.

Fig. 3. NASA database wind data in Sonzapote and wind data of closest meteorological stations

Fig. 4. Daily variation of the wind speed (left) and the wind rose (right) as by anemometer data

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.

Fig.7. Main components of a hybrid wind-PV electrification system (Ranaboldo et al., 2014c).

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.

Fig. 9. The intermediate costs configuration (Scenario 2).

Figure 1

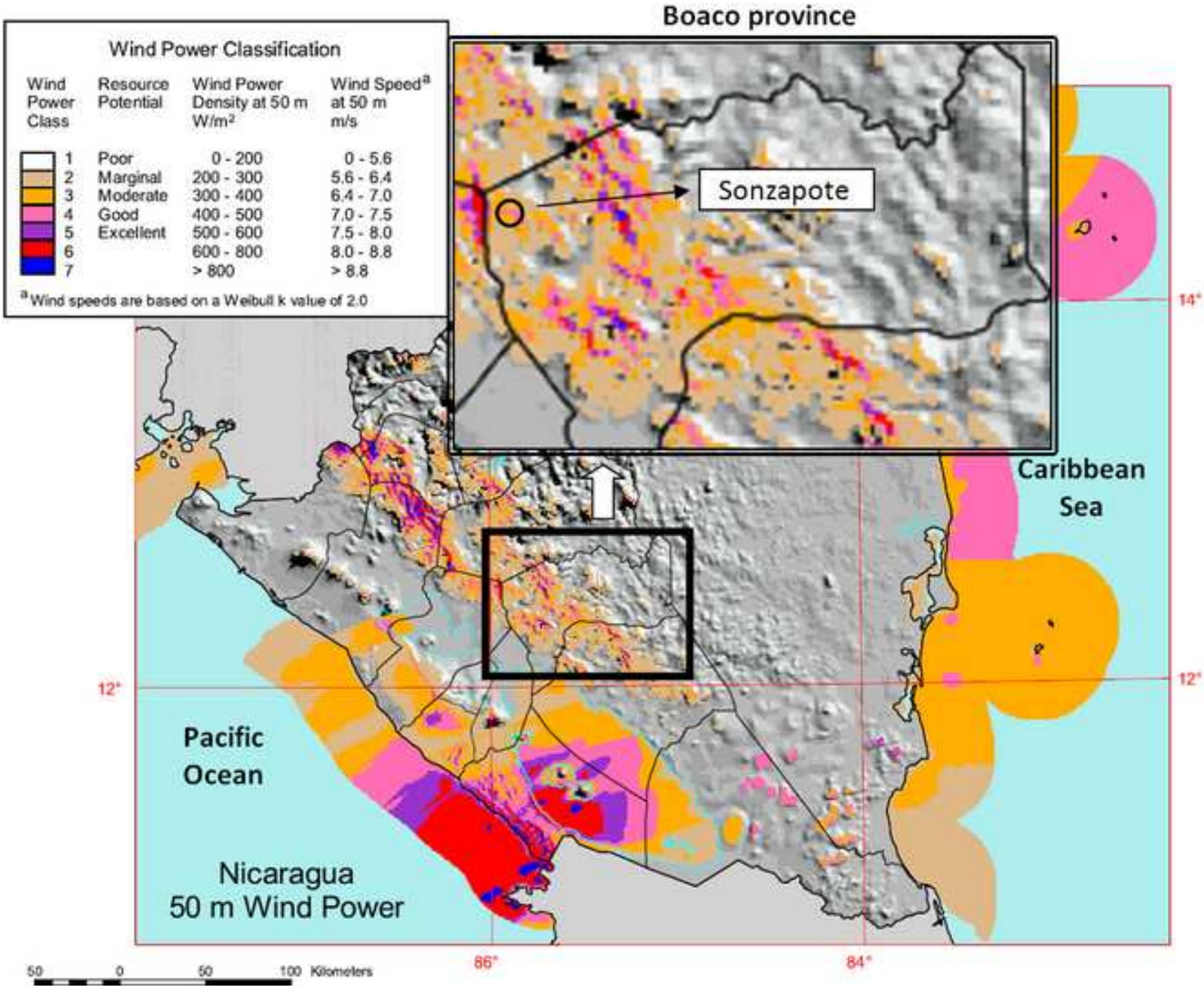
Boaco province
Wind Power Classification
Wind Power Class
Resource Potential
Wind Power Density at 50 m W/m²
Wind Speed[a] at 50 m m/s
1 Poor 0 - 200 0 - 5.6
2 Marginal 200 - 300 5.6 - 6.4
3 Moderate 300 - 400 6.4 - 7.0
4 Good 400 - 500 7.0 - 7.5
5 Excellent 500 - 600 7.5 - 8.0
6 600 - 800 8.0 - 8.8
7 > 800 > 8.8
[a] Wind speeds are based on a Weibull k value of 2.0
Sonzapote
Caribbean Sea
Pacific Ocean
Nicaragua 50 m Wind Power
14°
12°
12°
86°
84°
50 0 50 100 Kilometers

Figure 3

Click here to download high resolution image

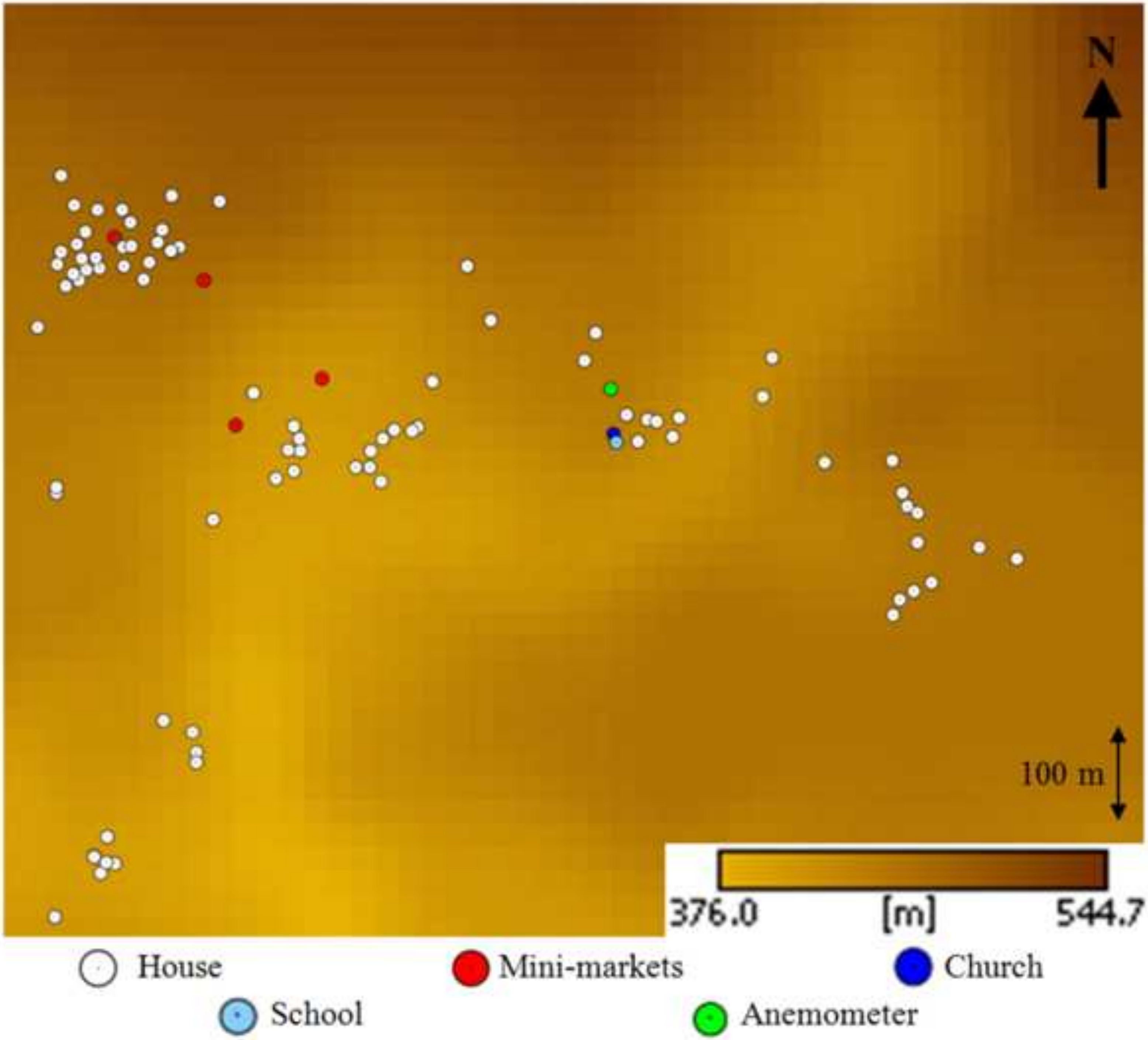

Figure 3

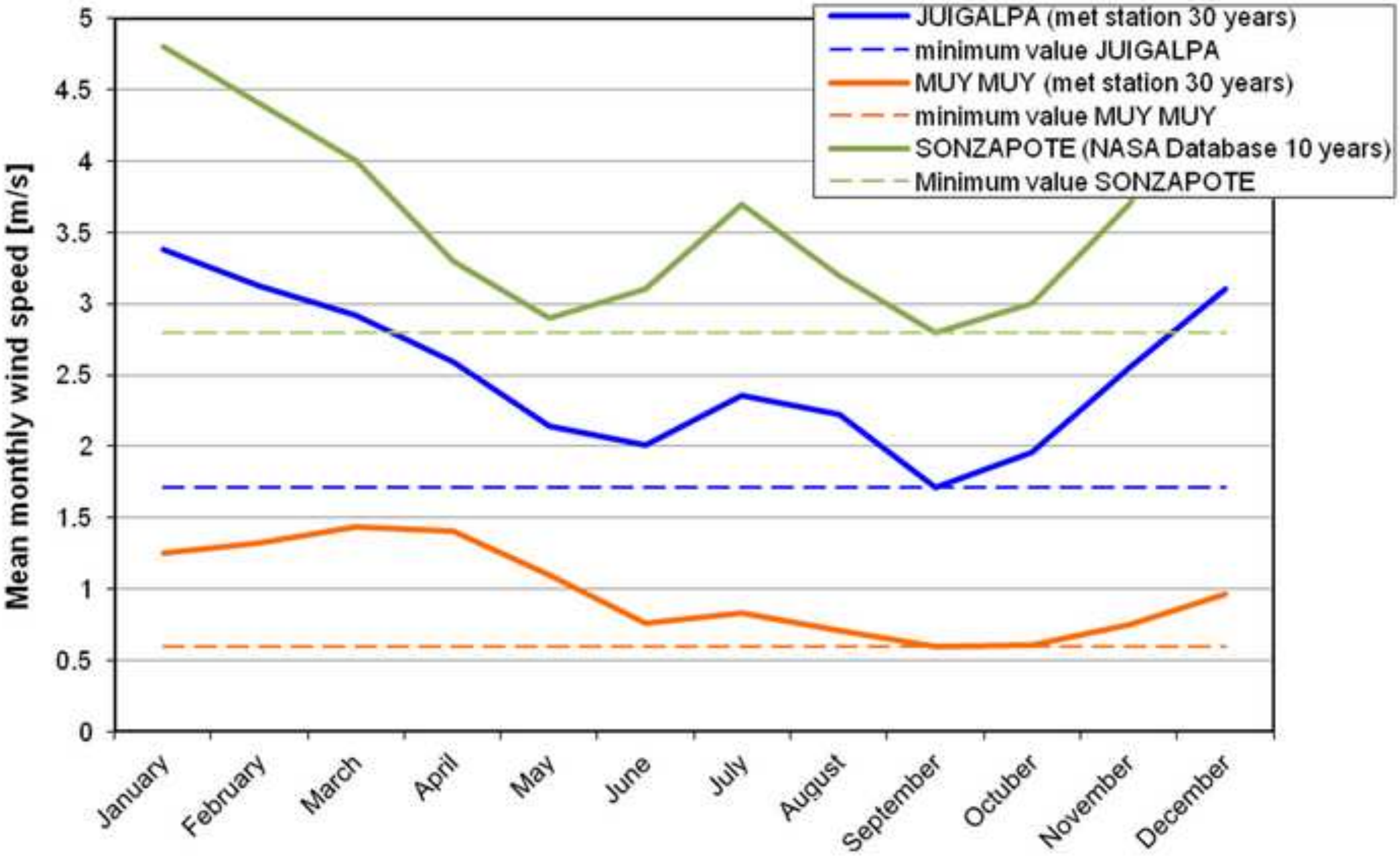
Mean monthly wind speed [m/s]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
January
February
March
April
May
June
July
August
September
Octuber
November
December
JUIGALPA (met station 30 years)
minimum value JUIGALPA
MUY MUY (met station 30 years)
minimum value MUY MUY
SONZAPOTE (NASA Database 10 years)
Minimum value SONZAPOTE

Figure 4


8.5 m Speed
Wind Speed (m/s)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
16
18
20
22
Hour
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
10 %
20 %
30 %
40 %
50 %
60 %
Percent of Total Time
Percent of Total Energy

Figure 5

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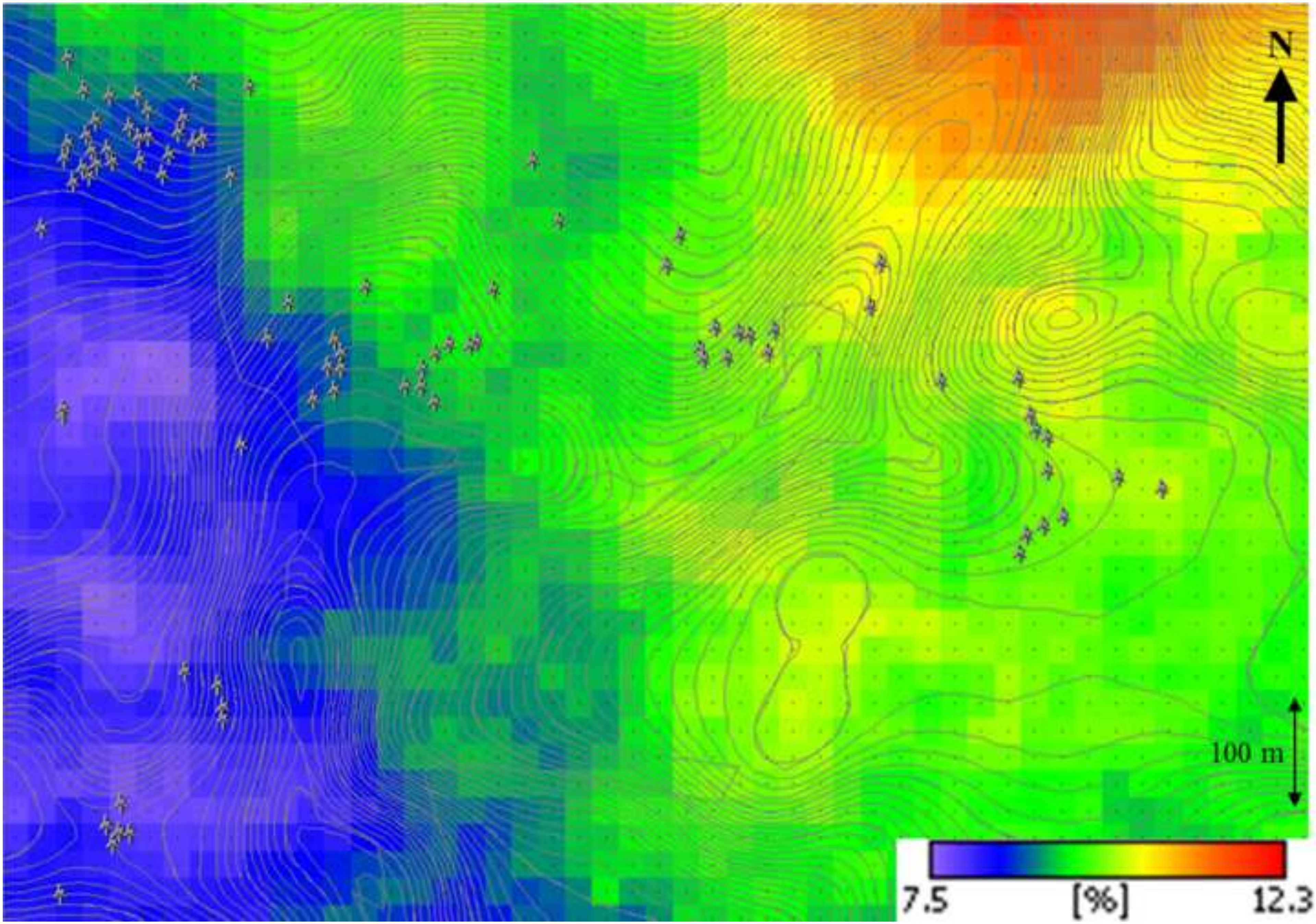


Figure 6

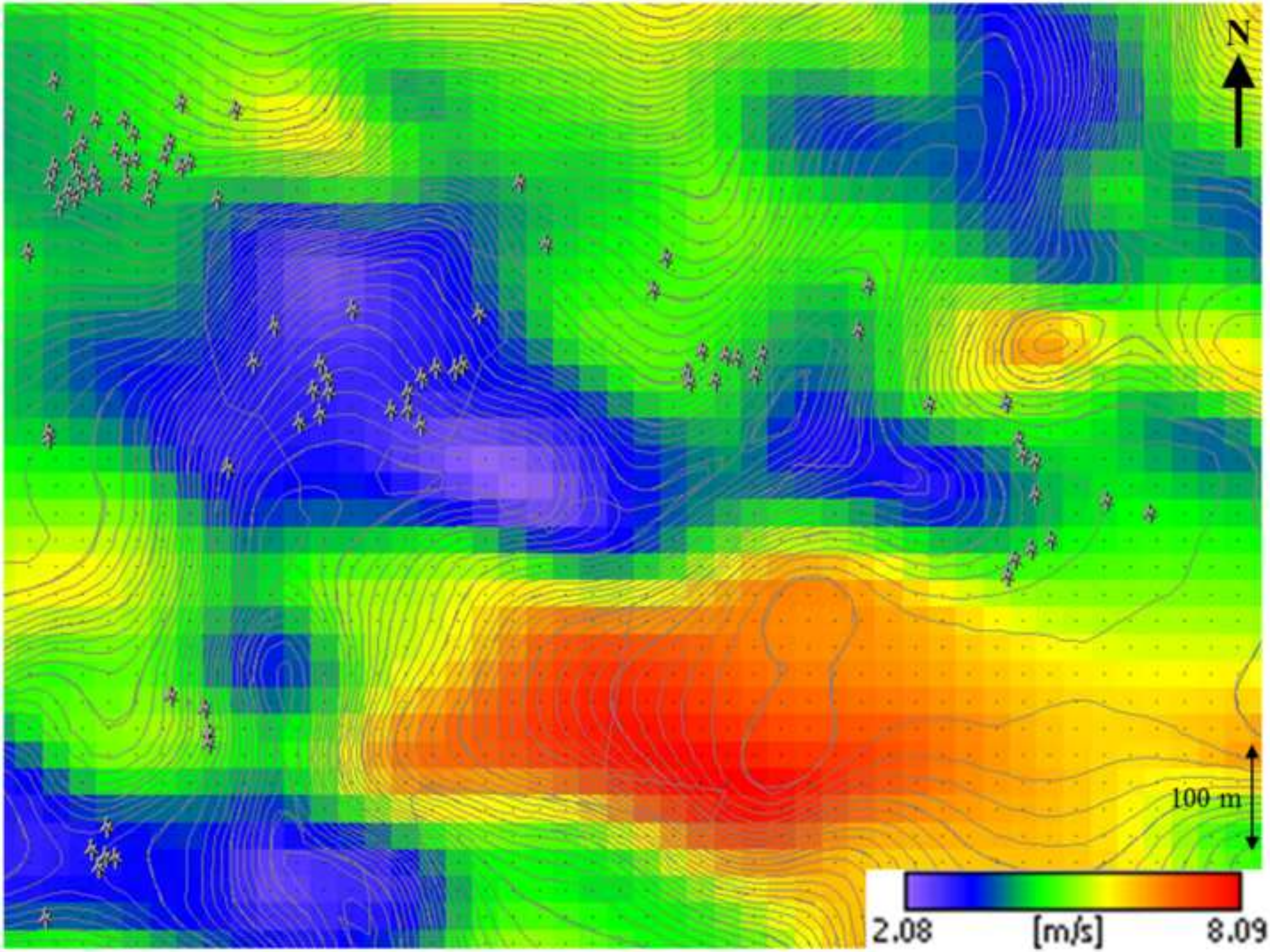


Figure 7

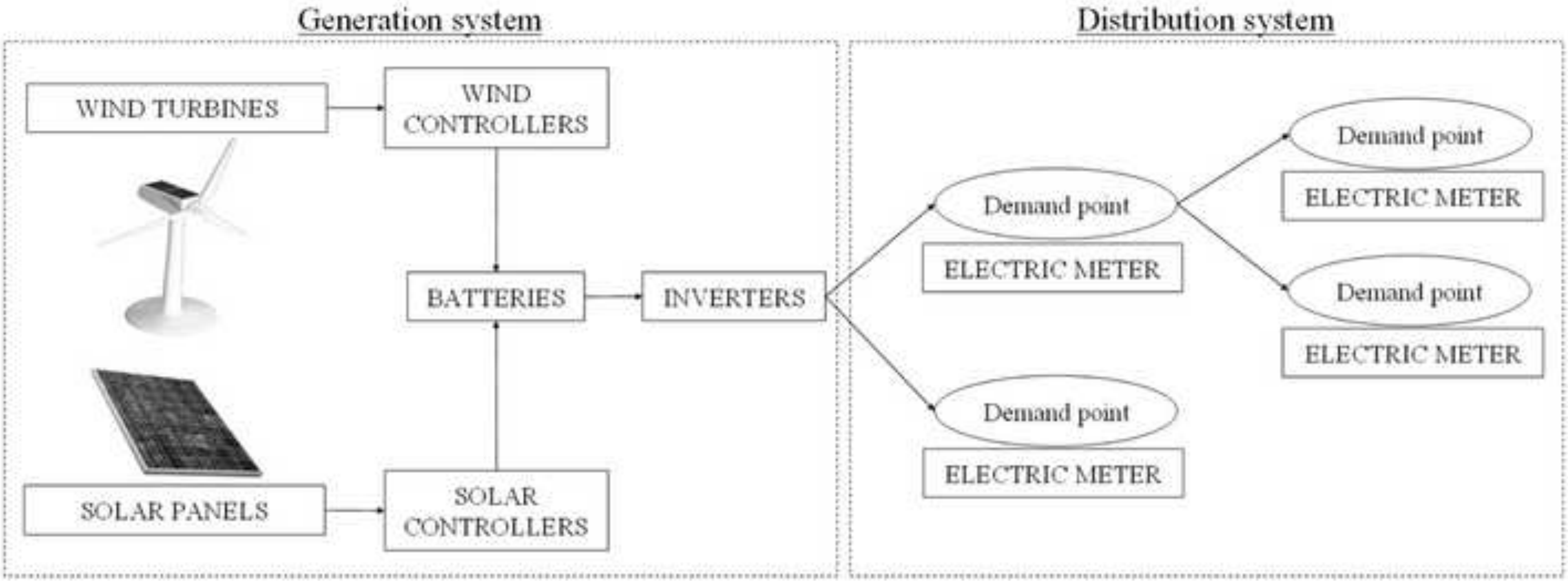

Generation system
Distribution system
WIND TURBINES
WIND CONTROLLERS
BATTERIES
INVERTERS
SOLAR PANELS
SOLAR CONTROLLERS
Demand point
ELECTRIC METER
Demand point
ELECTRIC METER
Demand point
ELECTRIC METER
Demand point
ELECTRIC METER

Figure 8

Click here to download high resolution image

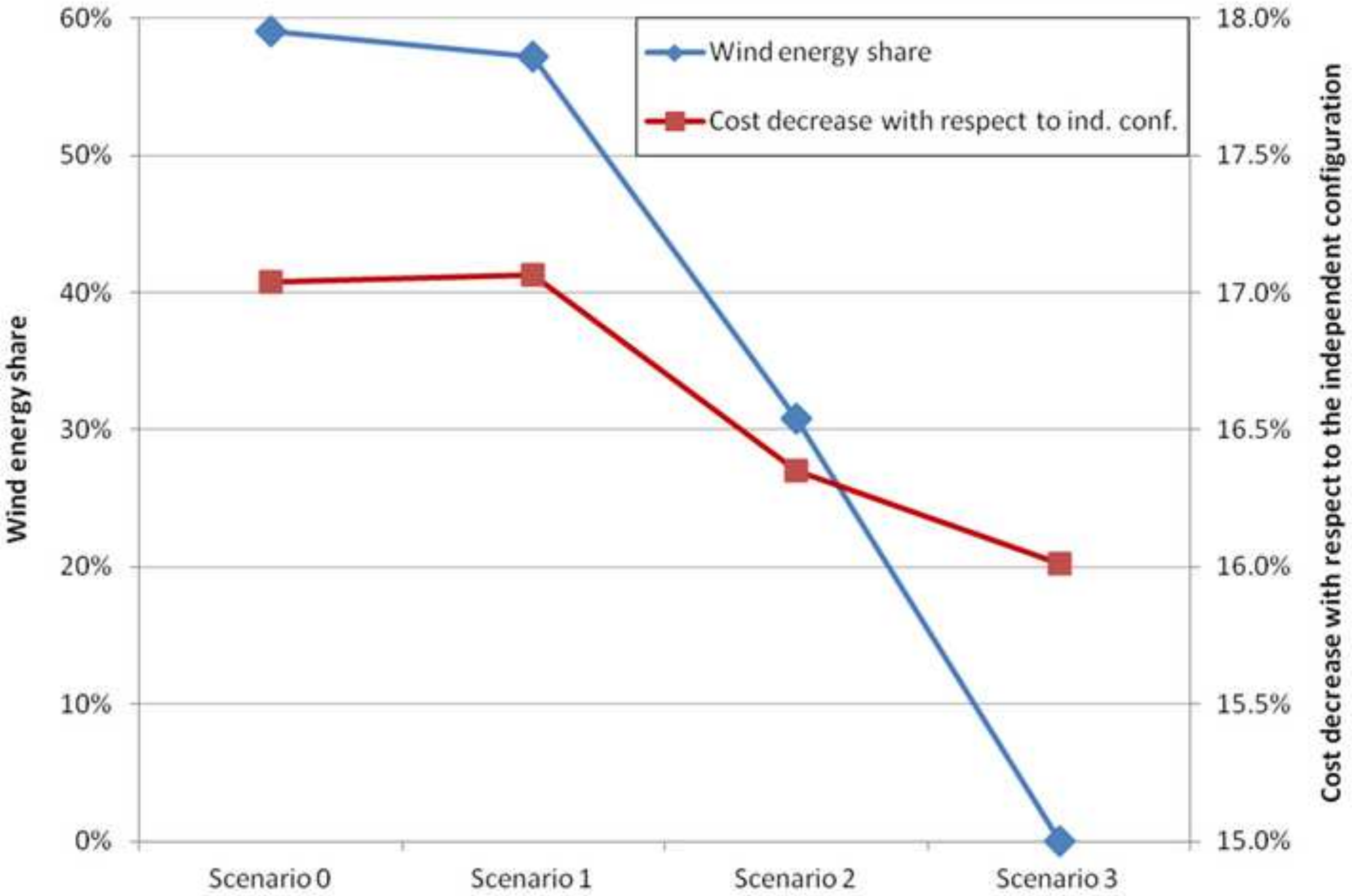
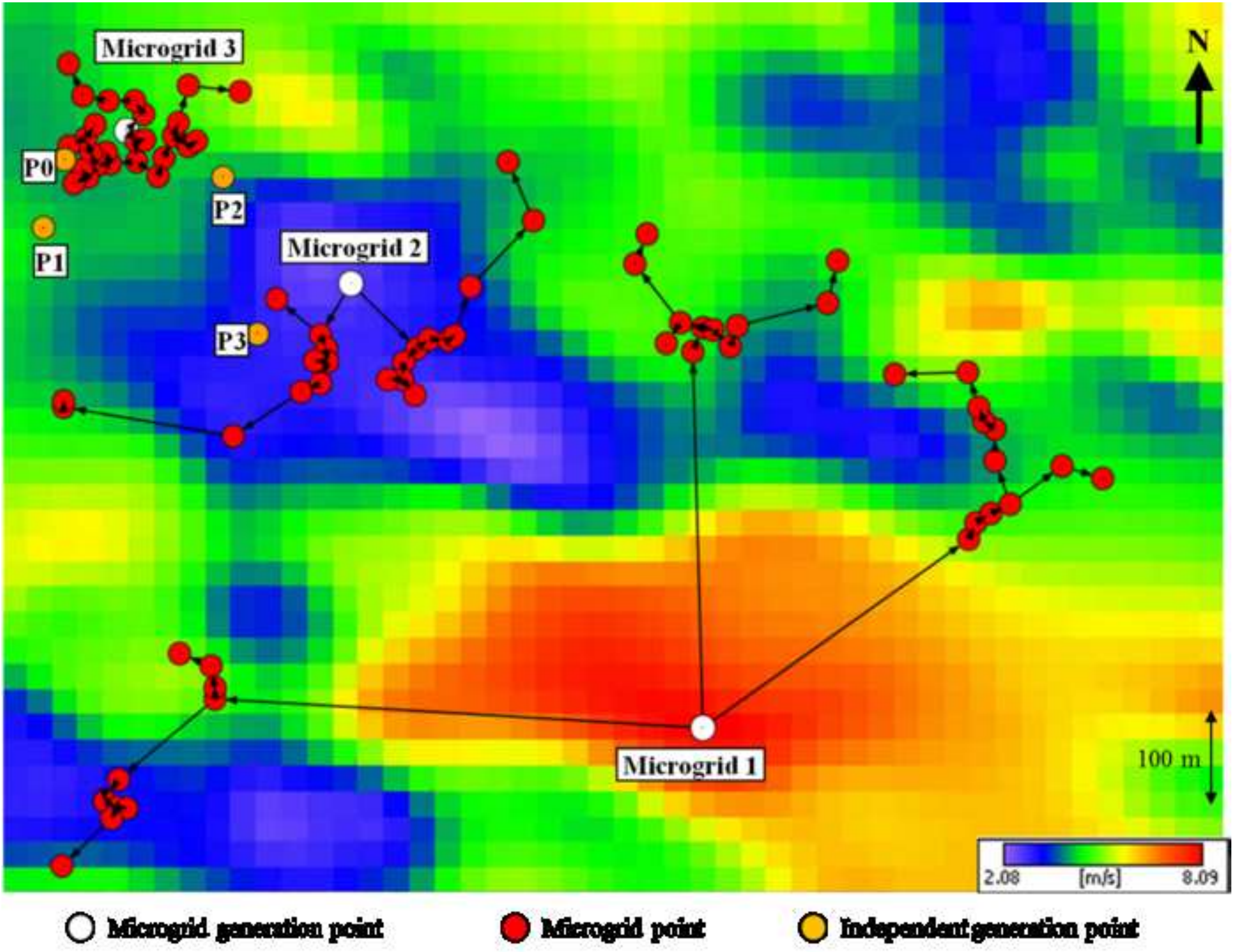


Figure 9


Microgrid 3
N
P0
P2
P1
Microgrid 2
P3
Microgrid 1
100 m
2.08
[m/s]
8.09
Microgrid generation point
Microgrid point
Independent generation point

Journal name: Solar Energy
Manuscript title: Off-grid community electrification projects based on wind and solar energies: a case study in Nicaragua

Tables

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

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 Maximum discharge rate: 0.6 Days of autonomy: 2
Type 2	2520	300	
Type 3	25200	3000	
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

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

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.