Renewable energy projects to electrify rural communities in Cape Verde

Matteo Ranaboldo[1*], Bruno Domenech Lega[2], David Vilar Ferrenbach[3], Laia Ferrer-Martí[1], Rafael Pastor Moreno[2], Alberto García-Villoria[2]

1 Department of Mechanical Engineering, Technical University of Catalonia, Av. Diagonal 647, Barcelona, Spain
2 Institute of Industrial and Control Engineering, Technical University of Catalonia, Av. Diagonal 647, Barcelona, Spain
3 ECOWAS Centre for Renewable Energy and Energy Efficiency, Praia, Cape Verde

NOTICE: this is the author's original version of a work that was submitted for publication in Applied Energy. The definitive version was subsequently published in: 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. http://dx.doi.org/10.1016/j.apenergy.2013.12.043

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. First a detailed wind resource assessment is carried out utilizing meso-scale wind atlas data combined with 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. 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 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 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 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 pollutants emission.

[*] *Corresponding author e-mail:* matteo.ranaboldo@upc.edu
Postal address: Av. Diagonal, 647, Pavilion F, floor 0, 08028, Barcelona, Spain. *Tel:* +34.934016579

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 in 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 consumption does not depend on the resource in its location. Second, equity between user consumptions is improved by relying on the same generators. 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. 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 [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 focus basically on defining the best combination of renewable generation sources [11, 12, 13, 14], while just a few focus on the optimal design of microgrids and the definition of the system [10, 15]. 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]. ViPOR [16] 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 high solar radiation during the whole year. Furthermore, tropical trade winds are well developed over most of Cape Verde islands and exposed sites have an important wind resource [17, 18]. 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, 18, 19, 20].

In this study, design analyses of off-grid electrification projects based on wind and solar power are carried out in 3 rural communities of Cape Verde. The analyzed communities are Figueiras and Ribeira Alta in the island of Santo Antão, and Achada Leite in the island of Santiago. A recent study [2] proposes the replacement of current diesel systems in Figueiras and Ribeira Alta with hybrid systems combining diesel, wind and solar energy. 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 community area. Therefore, the design of the projects was just preliminary and mainly focused on the economical comparison with current diesel systems. In fact, recent electrification projects in areas with complex topography, as the studied communities, confirmed that high wind resource differences could be present between houses of a community [21] and detailed wind resource studies are required. Hereby, a high resolution wind resource assessment is carried out by the use of a specific wind flow model that takes into account real topographical wind speed changes. The solar resource is considered uniform at the micro-scale of the studied areas. The mentioned MILP model [10] is then applied in order to optimize microgrids' configuration and generators locations. The final proposed electrification system is totally based on renewable energy, takes advantage of best resource areas and results to be economically reliable in comparison with a diesel generator system.

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".

The solar resource of Cape Verde is high and uniform among the islands with a mean global irradiance varying between 5 and 7 $kWh/(m^2 \cdot day)$ along the year [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 (4.8 $kWh/(m^2 \cdot day)$ as by NASA climate database [22]) is considered in this study.

The wind climate of the country is the typical of sub-tropical region with trade winds prevailing: dominant wind direction is from the northeast and is basically constant along the year. A meso-scale wind resource map of the whole country is available [17], 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 (around 5.5 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 [17]. 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 mean monthly 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. As a high variability of the wind recourse is expected in hilly terrain even at a micro-scale [21], a detailed assessment is carried out in Section 3.

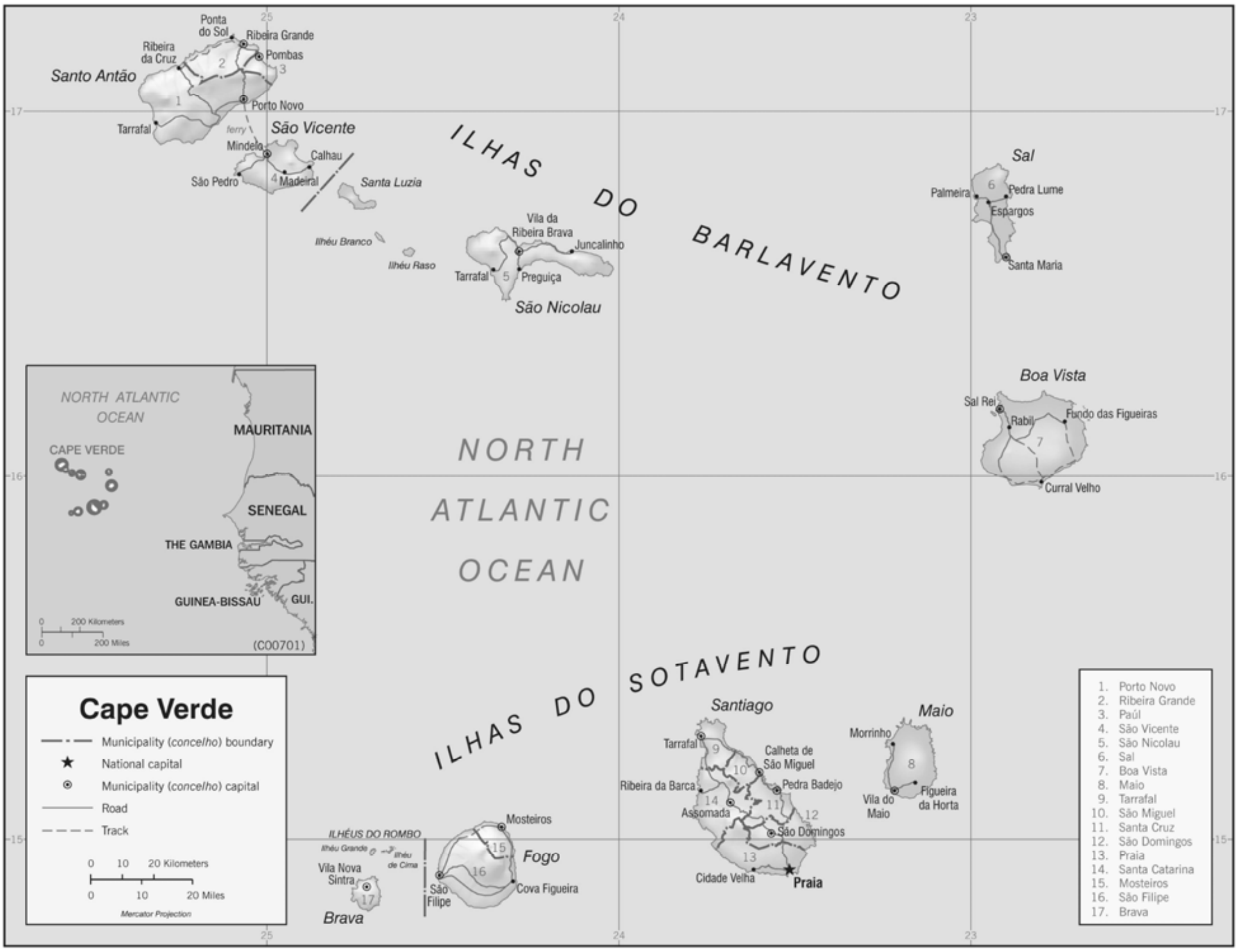

Fig.1. Cape Verde map

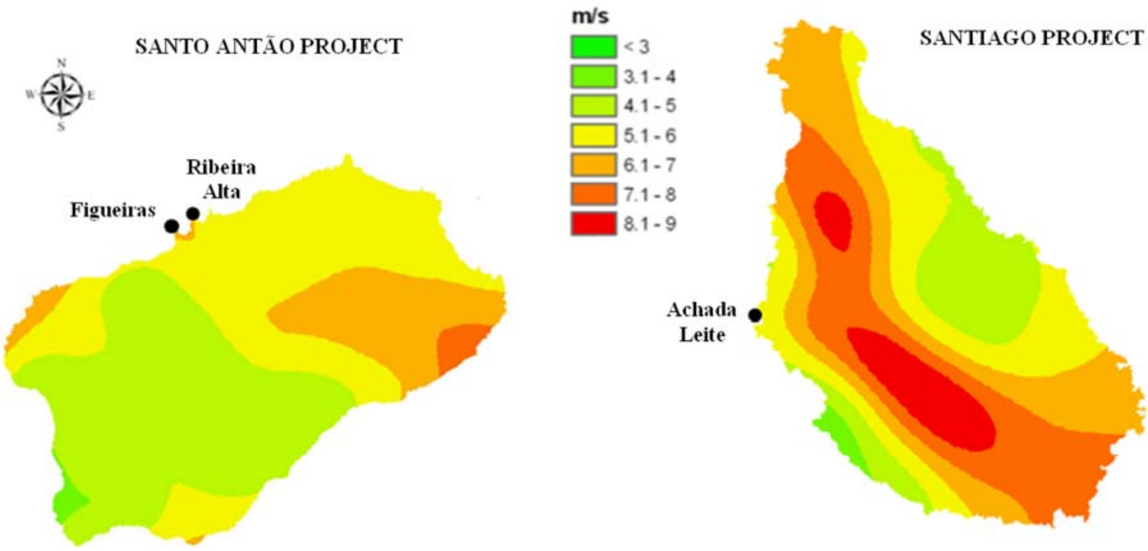

Fig.2. Mean wind speed at 50 m in Santo Antão and Santiago Islands [17]. Black point indicates studied communities' locations

2.1. *Santo Antão project*

Figueiras and Ribeira Alta communities are located in two consecutive valleys on the nothern coast of Santo Antão. The distance between the 2 communities is around 1 km. The communities of Figueiras and Ribeira Alta are composed by 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 micro-grids (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 far from analyzed communities. The uncertainty of this assumption is high as the wind climates of the 2 islands could be 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 micro-grids 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 (in a straight line) in mountainous terrain. To our knowledge, no previous study on the design of 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, same input data (in terms of houses 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 [17]. In order to evaluate the wind resource with higher detail a micro-scale analysis is carried out with WAsP software [25], 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) in order to site turbines and its operational limits are well known [26]. 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. It was verified that, with good input data, WAsP estimation error is limited for rural communities' studies in medium complex terrain [21].

The wind resource is modeled at 20 m a.g.l. that 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 [17] 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, in order to consider less windy month of the year, a decrease of 10% on the mean wind speed is applied to wind atlas average values [17].

3.1 Santo Antão project

Figueiras and Ribeira Alta are located in two valleys with areas of abrupt terrain in Santo Antão Island (Figure 3). 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 fiords, 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 Figure 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 [25].

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.

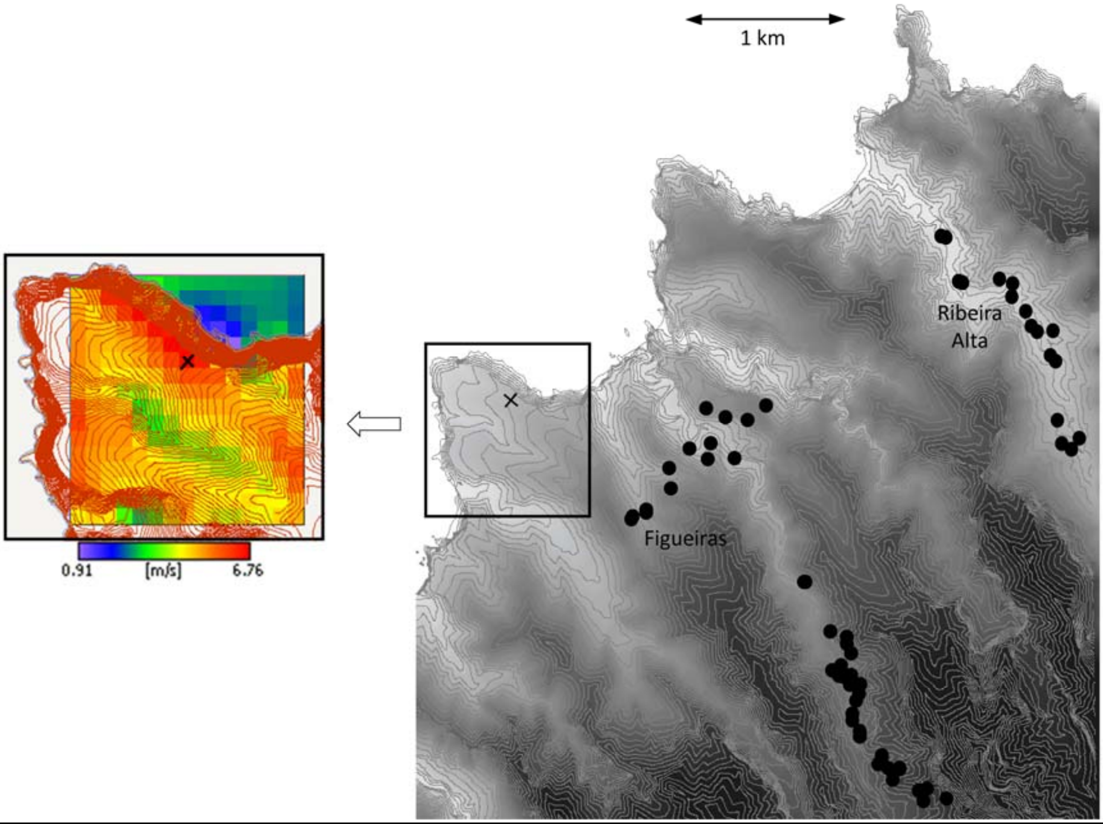

Fig.3. Santo Antão project topography (right) and mean wind speed at 20 m a.g.l. in the smooth hill close to Figueiras (left). Users' positions are shown by black circles. The "X" indicates the selected wind generation point

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 [25].

Resulting wind resource map (Fig. 4) shows high resource variability 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 for 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.

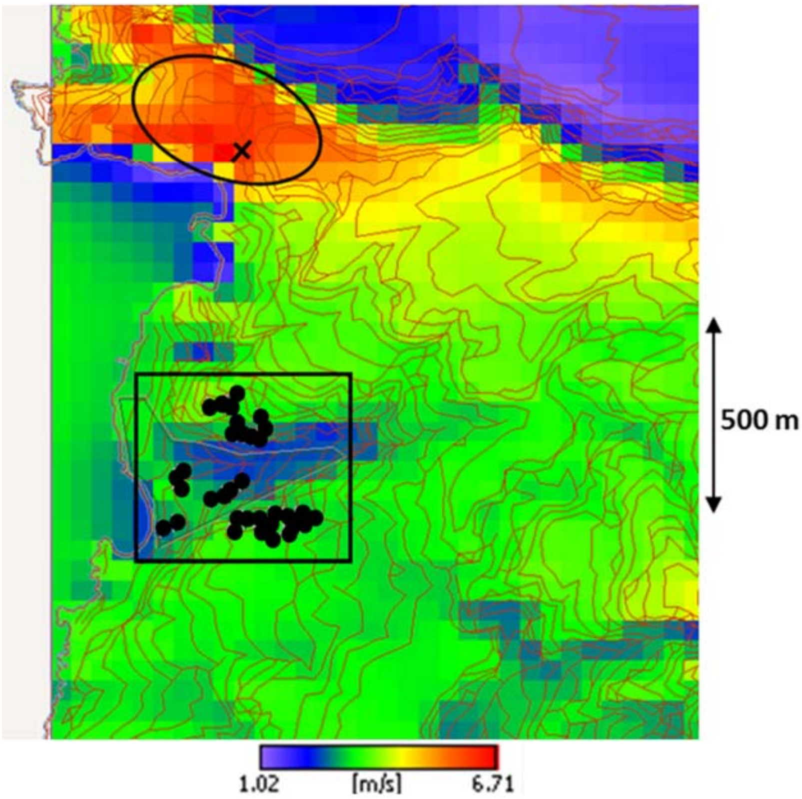

Fig.4. Mean wind speed at 20 m a.g.l. in Santiago project area. Community houses and school positions are shown by black circles. The "X" indicates the selected wind generation point

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.

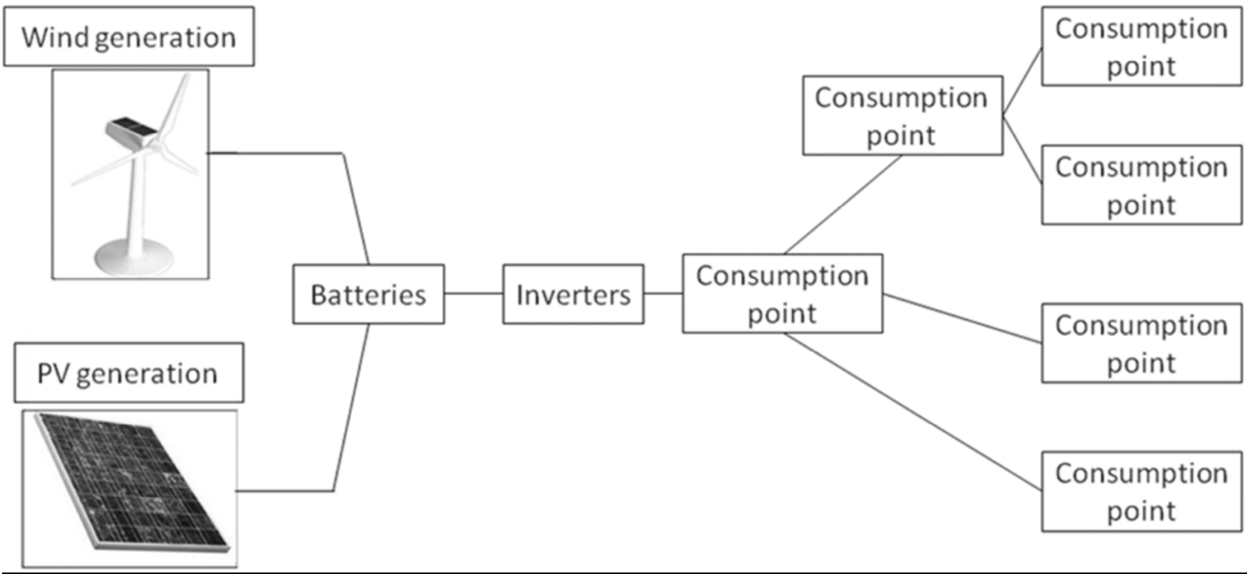

Fig.5. Scheme of the elements involved in a hybrid wind-PV electrification system [10]

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 [27] (form of a tree as in Fig. 5).
- Every consumption point has its own energy and power demand. 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

Integer programming has gained acceptance as a tool for providing optimal or near-optimal solutions to real-life strategic and operational planning problems [28]. In this sub-Section a mixed integer linear programming (MILP) model for the design optimization of an electrification system is summarized [10]; the model is then applied for the design of Santo Antão and Santiago projects (Section 5).

The MILP model allows designing stand-alone electrification systems for rural communities with wind-PV energies and aims to minimize the cost of the initial investment, a critical limitation in this type of projects [3]. The model takes into account the configuration of the system and technical criteria of the equipment that may be used (for more details see [10]). The MILP is divided into parameters, variables, objective function and constraints:

- 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.
- Constrains:
  - *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 Figure 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

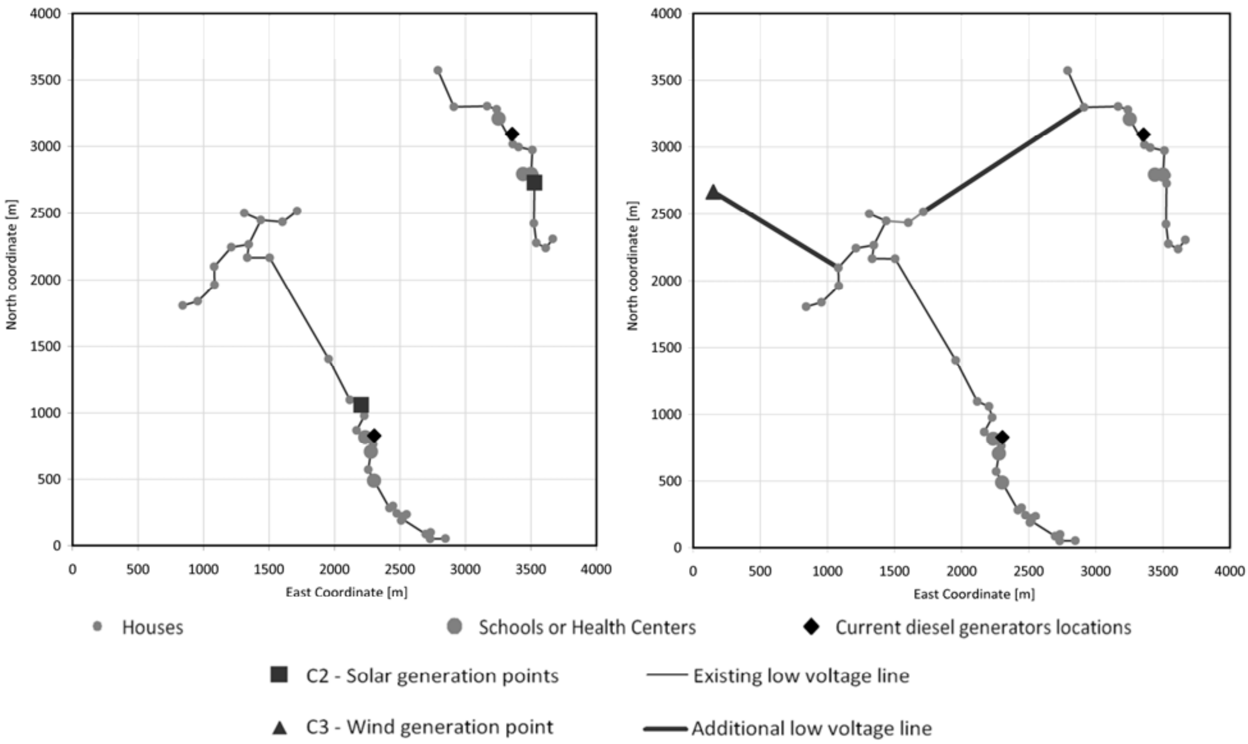

Fig.6. Configurations C2 (left) and C3 (right) for the electrification of Santo Antão project

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).

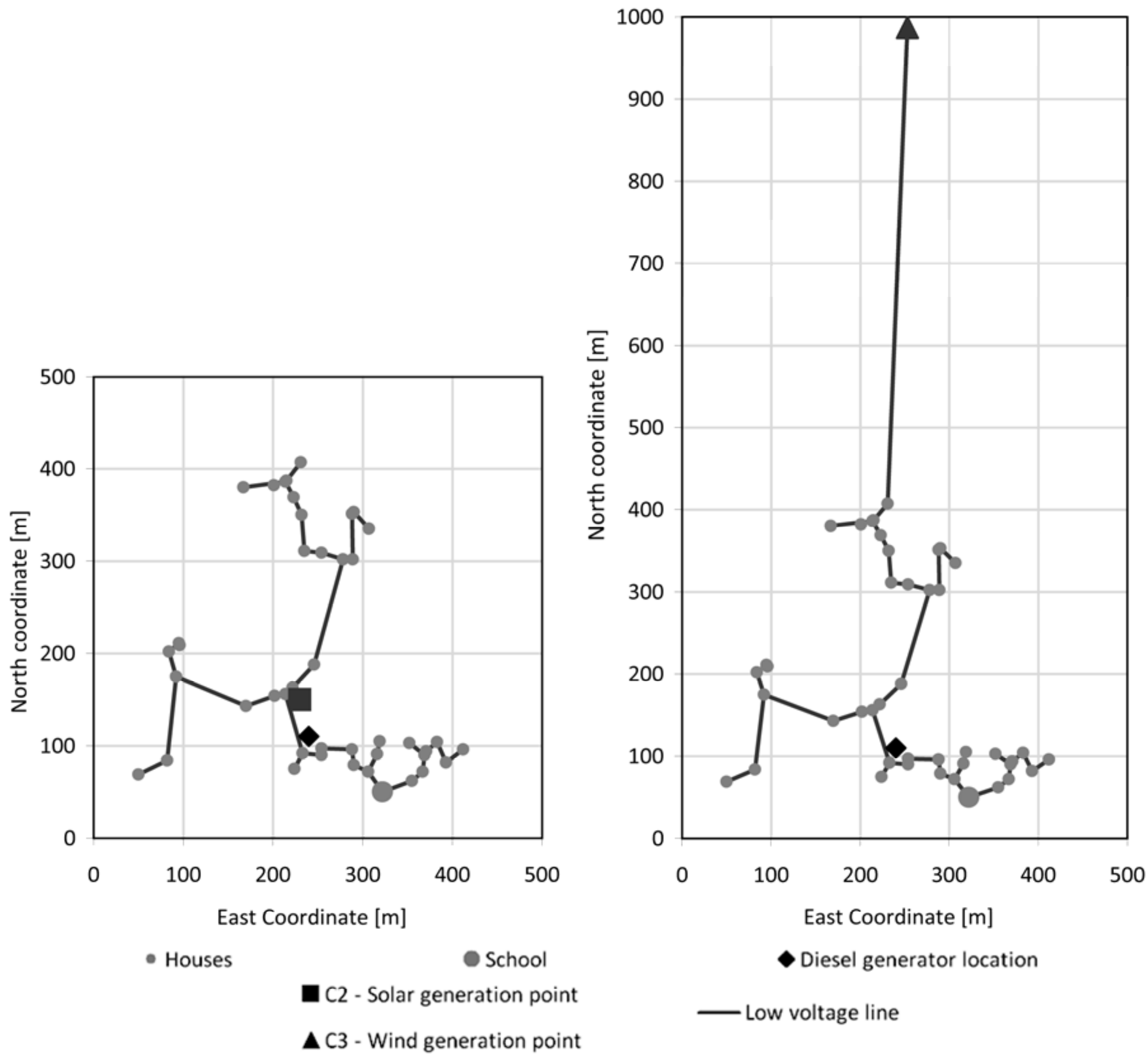

Fig.7. Configurations C2 (left) and C3 (right) for the electrification of Santiago project

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 in 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 hereby 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 micro-grid 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

<table>
<tr><th></th><th></th><th colspan="2">Santo Antão project</th><th colspan="2">Santiago project</th></tr>
<tr><th></th><th></th><th>Proposed configuration</th><th>Diesel configuration</th><th>Proposed configuration</th><th>Diesel configuration</th></tr>
<tr><td rowspan="3">Initial investment</td><td>Equipment</td><td>297594</td><td>0</td><td>90380</td><td>18274</td></tr>
<tr><td>T & I & TA</td><td>106429</td><td>0</td><td>31929</td><td>15964</td></tr>
<tr><td>Total</td><td>404023</td><td>0</td><td>122388</td><td>34238</td></tr>
<tr><td rowspan="4">Annual Costs</td><td>Equipment replacement</td><td>6192</td><td rowspan="2">24429</td><td>1700</td><td rowspan="2">5938</td></tr>
<tr><td>O & M</td><td>5000</td><td>1500</td></tr>
<tr><td>Fuel</td><td>0</td><td>21767</td><td>0</td><td>5291</td></tr>
<tr><td>Total</td><td>11192</td><td>46195</td><td>3200</td><td>11230</td></tr>
</table>

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.

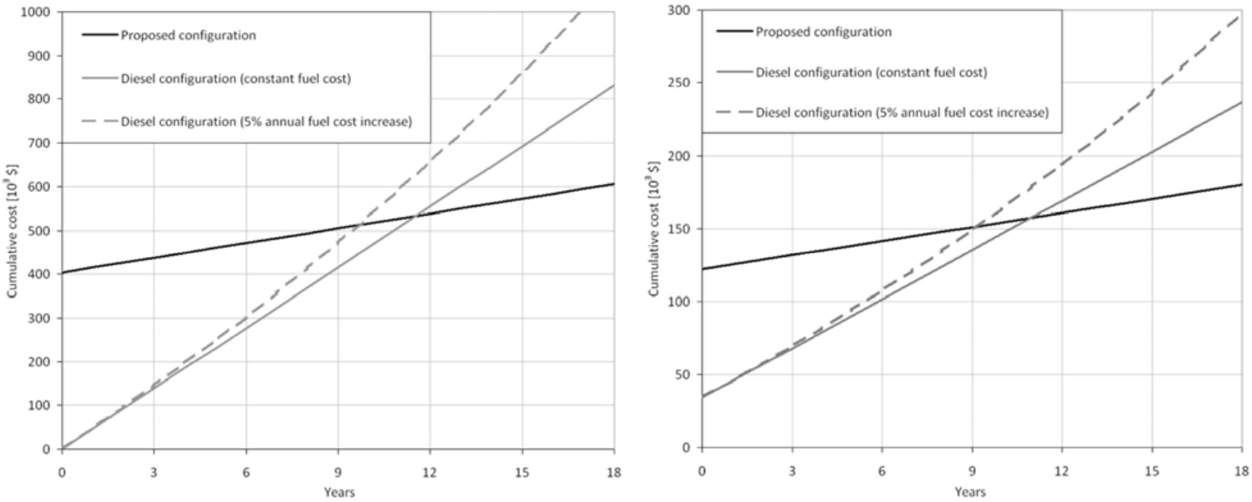

Fig.8. Cumulative costs' evolution of the proposed and diesel configurations in Santo Antão (left) and Santiago (right) projects

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 [17]) 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.

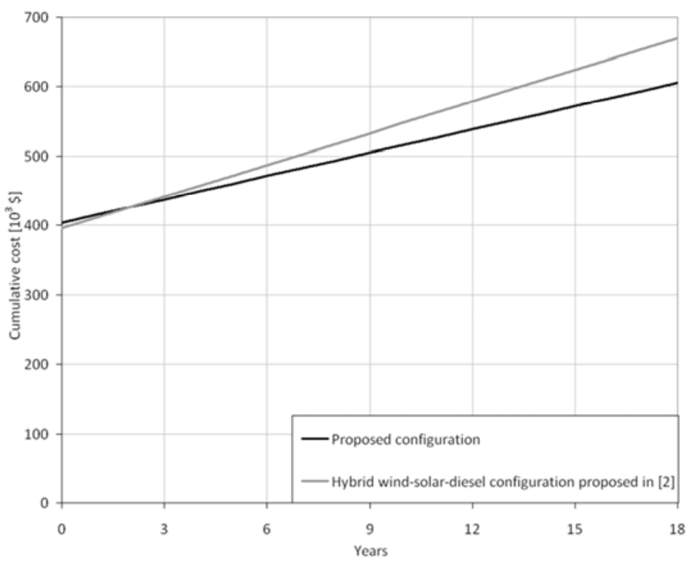

Fig.9. Cumulative costs' evolution of the proposed configuration and the system proposed in [2] in Santo Antão project

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 side, the utilization of a diesel generator leads to the emission of different contaminant gases, such as SOx, NOx and CO_2 [29]. Considering only carbon dioxide emission, assuming an emission rate of 0.65 kg CO_2 / net-kWh [29], 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 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 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.

References

[1] Briceño-Garmendia CM, Benitez DA. Cape Verde's infrastructure, A continental perspective, The World Bank Africa Region Sustainable Development Department, Policy Research Working Paper 5687, June 2011.

[2] Raimundo C, Branfield H, Mestre J. Pre-feasibility report for electrification of Figueiras and Ribeira Alta with hybrid systems, Global Environmental Facility, November 2010.

[3] Erdinc O, Uzunoglu M. Optimum design of hybrid renewable energy systems: Overview of different approaches, Renewable and Sustainable Energy Reviews 2012;16:1412– 25.

[4] Zhou W, Lou C, Li Z, Lu L, Yang H. Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems. Applied Energy 2010;87(2):380-9.

[5] Ferrer-Martí L, Pastor R, Capo M, Velo E. Optimizing microwind rural electrification projects. A case study in Peru, Journal of Global Optimisation 2011;50:127-43.

[6] Leary J, While A, Howell R. Locally manufactured wind power technology for sustainable rural electrification. Energy Policy 2012;43:173-83.

[7] Lemaire X. Off-grid electrification with solar home systems: The experience of a fee-for-service concession in south africa. Energy for Sustainable Development. 2011;15(3):277-83.

[8] Kirubi C, Jacobson A, Kammen DM, Mills A. Community-based electric microgrids can contribute to rural development: evidence from Kenya, World Development 2009;37:1208–21.

[9] Nfah EM, Ngundam JM, Vandenbergh M, Schmid J. Simulation of off-grid generation options for remote villages in Cameroon. Renewable Energy 2008;33(5):1064-72.

[10] Ferrer-Martí L, Domenech B, García-Villoria A, Pastor R. A MILP model to design hybrid wind-photovoltaic isolated rural electrification projects in developing countries, European Journal of Operational Research 2013;226:293-300.

[11] Saheb-Koussa D, Haddadi M, Belhamel M. Economic and technical study of a hybrid system (wind-photovoltaic-diesel) for rural electrification in Algeria. Applied Energy 2009;86(7-8):1024-30.

[12] Bekele G, Tadesse G. Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in ethiopia. Applied Energy 2012;97(0):5-15.

[13] Akella AK, Sharma MP, Saini RP. Optimum utilization of renewable energy sources in a remote area, Renewable and Sustainable Energy Reviews 2007;11:894-908.

[14] Aagreh Y, Al-Ghzawi A. Feasibility of utilizing renewable energy systems for a small hotel in ajloun city, jordan. Applied Energy 2013;103(0):25-31.

[15] Ter-Gazarian AG, Kagan N. Design model for electrical distribution systems considering renewable, conventional and energy storage units, IEE Proceedings-C Generation, Transmission and Distribution 1992;139:499-504.

[16] Lambert TW, Hittle DC. Optimization of autonomous village electrification systems by simulated annealing, Solar Energy 2000;68:121-32.

[17] Numerical Wind Atlas Study for Cape Verde, Risø National laboratory, 16th March 2007.

[18] Chen F, Duic N, Manuel Alves L, da Graça Carvalho M. Renewislands—Renewable energy solutions for islands. Renewable and Sustainable Energy Reviews 2007;11(8):1888-902.

[19] Duic N, Alves LM, Chen F, da Graça Carvalho M. Potential of kyoto protocol clean development mechanism in transfer of clean energy technologies to small island developing states: Case study of cape verde. Renewable and Sustainable Energy Reviews 2003;7(1):83-98.

[20] Segurado R, Krajaĉic G, Duić N, Alves LM, Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde, Applied Energy 2011;88:466-72.

[21] 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.

[22] NASA Surface meteorology and Solar Energy, Release 6.0 Version 3.0, April 2011. http://eosweb.larc.nasa.gov/sse/. Accessed 27th of March 2012.

[23] Gueymard CA, Wilcox SM. Assessment of spatial and temporal variability in the US solar resource from radiometric measurements and predictions from models using ground-based or satellite data. Solar Energy 2011;85(5):1068-84.

[24] Frank HP, Rathmann O, Mortensen NG, Landberg L. The numerical wind atlas – the KAMM/WAsP method, Risø National Laboratory, Roskilde, Denmark, 2001.

[25] Mortensen NG, Heathfield DN, Myllerup L, Landberg L, Rathmann O. Wind atlas analysis and application program: WAsP 9 help facility, Risø National Laboratory, Roskilde, Denmark, 2007.
[26] Bowen AJ, Mortensen NJ. WAsP prediction errors due to site orography, Risø National Laboratory, Roskilde, Denmark, 2004.
[27] Alzola JA, Vechiu I, Camblong H, Santos M, Sall M, Sow G. Microgrids project, Part 2: Design of an electrification kit with high content of renewable energy sources in Senegal. Renewable Energy 2008;34(10):2151-9.
[28] Atamtürk A, Savelsbergh MWP. Integer-programming software systems, Annals of Operations Research 2005;140:67–124.
[29] Energy Sector Management Assistance Program (ESMAP), Technical and economic assessment of off-grid, mini-grid and grid electrification technologies, Washington DC, 2007.