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Mas Roig Mini-Grid: A Renewable-Energy-Based Rural Islanded Microgrid

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***Abstract*—This paper presents a microgrid project, named Basic Distributed Nodes (NoBaDis), deployed in a stand-alone farm in Girona, Spain. NoBaDis is based on intensive use of information to maximize the penetration of renewable energy through two main strategies: anticipation and opportunity. The loads are classified in four different types according to priority and are controlled by intelligent sockets interconnected in a mesh network. Each socket measures the main electric parameters, communicates to the local computer bidirectionality by using ZigBee communications, and is able to switch on/off the loads. The power system is composed by low-density energy sources (renewable) and high-density cogeneration engine. These elements can be interconnected in two different configurations to test different scenarios. After 5 years of operation, the results has shown the importance of real-time management system to reduce the operational costs of the microgrid. In addition the project has highlighted the importance of distributed generation and control to assure the energy supply in terms of quality and quantity even in extremely weather conditions as it was in March 2010 during a snow storm that generated a black out that affected more than 250,000 consumers in this area during one week.**

Keywords: Islanded Microgrid, renewable energy, rural electrification, minigrid.

I. Introduction

MICROGRID is an attractive concept when trying to integrate renewable energy resources in agricultural or rural areas [1]-[5]. In such an environments grid connection is sometimes impracticable or the grid connection is too weak, so that it can present higher impedance, flickers, temporary outages, and other power quality problems. In this sense, autonomous microgrids are presented as a suitable solution for islanded energy systems [6]-[10]. Sometimes microgrids are defined as an autonomous small grid that contains local loads, energy storage systems and distributed generators that can operate in both grid-connected and islanded modes [20]. However, microgrids were originally conceived as islanded systems to support remote areas or geographical islands that are not supported by the main grid. Islanded microgrids in rural areas often named *mini-grids* [21], [22].

One of the main problems in islanded microgrids is the mismatch between power generation and consumption, while increasing energy storage solution has the drawback of higher cost and size [11]. Consequently, active loads that can be shifted along time intervals can help to reduce this problem, so that communication systems are necessary when coordinating the different elements that conforms the microgrid [12].

Communications systems in microgrid have been become an issue. The lack of standards allows microgrid designers to use a sort of technologies available in ICT market [13]. Power line communications is one of the possible strategies, which avoids the use of dedicated communication channels, thus using the existing power lines. However, this technology presents drawbacks such as EMI issues, power electronics filter design may affect the quality of service, and so on [14]. Alternatively, wireless communications are in general more suitable for residential applications [12]. In case of microgrids and residential grids ZigBee (IEEE 802.15.4) is becoming more and more commonly in-use [15]. The advantage is the flexibility and interconnectivity with already existing equipment such as sensors or smart-meters [16].

Furthermore, multiagent systems technologies have been applied not only in large scale electrical power systems, such as Cell Project in Denmark [17], but also in islanded microgrids or mini-grids [18], [19].

In this paper, which is the continuation of our previous work [23], we present experimental results of the islanded rural farm site that includes all the necessary technology to operate autonomously. Multi-agent systems, wireless ZigBee communications, load-shifting and renewable energy are combined in a concept that is directly connected with the needs and natural resources of or the site farm. The Mas Roig mini-grid is a real living lab in which these technologies were applied in order to satisfy the electricity demand and at the same time considering the geographical location and its local resources.

This paper is organized as follows. Section II describes the microgrid site, including the environmental description, energy needs, and the electrical parts of the microgrid. Section III presents the microgrid control and communication system. Section IV shows the communication infrastructure of the real microgrid site. Section V outlines the conclusion.

II. Mini-Grid Site Description

The pilot mini-grid is located in Mas Roig, Girona, Spain and comprises of a country house, a small farm and a number of renewable energy generators (PV panels and a small wind turbine) and a set of batteries. The scope of this pilot site is to demonstrate that the local networks of renewable energy sources can operate and sustain themselves independently.

III. Microgrid Site Description

Mas Roig is an organic farm in Llagostera municipality, Girona (Catalonia, Spain), which contents several different activities related to science and nature, such as an astronomic observatory, a reconversion of Mediterranean forest, organic agriculture and animals as can be seen in Fig. 1. More than seven thousand people have been visiting the facilities, specifically students, and it has been the test-field for technological developments in solar energy granted by several international patents [24], [25] by two different start-ups such as *Wattpic Energia Intel.ligent, Ltd*.

From the electrical point of view, Mas Roig is independent from the national electrical grid, despite it is not so far from a point of connection to the grid, which can be found in less than 200 meters. Historically, Mas Roig was powered by a diesel engine in the mid-nineties when photovoltaic systems were installed. Since then, several improvements have been done toward the final project named "*NoBaDis*" (*Basic Distributed Nodes*) that is still supplying electricity the whole farm. NoBaDis concept is based in how nature manage energy flows and it is summarized as follows: "*maximize solar energy input, recycling materials and managing intensive use of information to achieve high efficiency and a resilient system*".

(a)

(b)

Fig. 1. Mas Roig islanded microgrid site.

This biomimetic concept has move on reality using available technology to learnt about the limits of these commercial equipment, to test different configurations and to disseminate the lessons learnt both in a technical and non-technical forums Mas Roig is in the press on a regular basis, has received more than 7, 000 visitors and the experience has been present in some conferences and technical magazines.

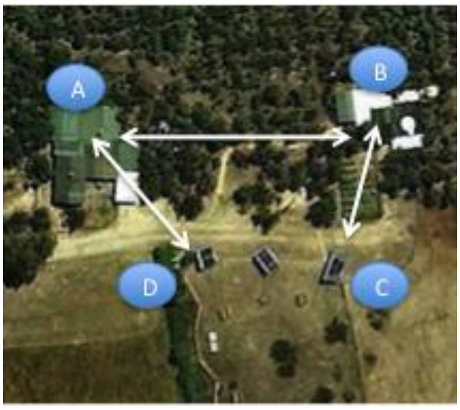
IV. Project Description

A. *Facility*

Mas Roig mini-grid is a real test site where a family is living in. The main activities are self-agriculture, sustainability divulgation activities (agriculture, forest, energy, wastes) and an Astronomy Observatory. There are several appliances and devices that have been organised depending on their priority (see Table I). The problem involves the consumption of 30 devices, classified in high, medium and low priority, depending on their characteristics. There is the possibility that one device can be used several times or that its use can be interrupted during the period of time is also considered.

The energy sources include a set of solar panels (2.5 kWp of aggregate photovoltaic mounted over a FA a patented [24] single axis tracker) and a micro-wind turbine (3 kWn). In addition to renewables, an independent micro-CHP (15 kVA) and the connection to the power grid are options that are also considered. Furthermore, a battery is considered (1400Ah C10), in order to storage energy. The production, storage and acquisition cost of energy are also taken into account.

Fig. 2 shows the consumption and generation facilities and the distance among them. A meshed network has installed to communicate the different elements.



Mas Roig facilities:
A – house
B – farm
C – PV#1 unit
D –PV#2 unit.

Distances:
AB 41m
AD 24m
BC 24m
BD 32m

Fig. 2. Microgrid configuration.

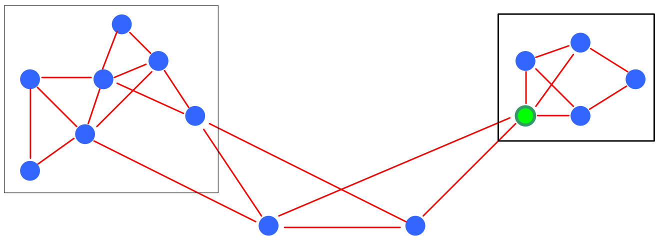


Fig 3. Meshed network based on ZigBee protocol.

TABLE I. LIST OF LOADS AND PRIORITIES

HIGH PRIORITY LOADS
• Lights on the living room (35 W) x2 • Light in the toilet (11W) • Refrigerator (90 W) • Pressure group (264 W) • Freezer (225 W)
MEDIUM PRIORITY LOADS
• Light on kitchen (24W) • Light on room (24W) x2 • Washing machine (750 W) • Tumble dryer (1200 W) • Vacuum Cleaner (1200 W) • Air Conditioning (258 W) x3 • Water pump (1000 W) • Water pump (750 W) • Computer iMAC (125 W)
LOW PRIORITY
• Entrance light (24 W) • Studio light (35 W) • Exterior lights (22 W)
MOBILE LOADS
• Microwave (1050 W) • Bread Toaster (1050 W) • Iron (1200 W) • Scanner (19 W) • Printer (44 W) • Fax (66 W) • Television (65 W) • Power Audio amplifier (10 W) • DVD (12 W)

B. *Loads*

The consumption loads in Mas Roig facilities can be divided into different types, based on a hierarchical priority scale. There are "*critical loads*" (always must be supplied by the microgrid), "*delayed loads*" (under pre-configured schedule), "*excess loads*" (non-electrical energy storage systems such as cooling or water high) and "*negotiable loads*" (potentially sold to another microgrid or to the main grid under a certain price schemes).

All the loads are interconnected trough the meshed ZigBee network, shown in Fig. 3. It includes 16 i-sockets, which are able to metering the electric parameters of the loads (active and reactive power, harmonics and voltage amplitude) as well as to connect/disconnect the loads according to the control strategy. There is a central controller implemented in a computer, which get all the microgrid data regarding generation and consumption, in order to manage the system by using specific software and executing the logic control to maximize the energy power-supply matching. The algorithm is based on minimum operation and maintenance cost.

- *High priority loads*: One node is used for the control of high priority loads. This node will be always measuring, and not controlling, yet the high priority loads should remain always connected (see Table II).
- *Medium priority loads:* All of them include a node that makes possible the on/off and the measurement of current (I) and voltage (V).
- *Low priority nodes (or static nodes):* previously settled up and constantly operating. All of them measure currents (I) and are able to switch *on* and *off*.
- *Mobile nodes*: they can appear or disappear, depending if the device is plugged in or not. Once the device is plugged in, it appears automatically into the Zig Bee system. Each device has to have a unique Zig Bee node associated in order to be able to record the consumption evolution and so on.

TABLE II. HIGH PRIORITY LOAD NODES

Load	*Consumption*	*Estimated distance (m)*	*Node No.*
Lights on the living room	35 W	40 indoors./outd.	1
Light in the toilett A-type freezer	11 W 90 Wh approx.	40 ind./outd. 5 ind.	
Pressure Group Tecno 05AM	180W/24h 264W/h. ½ hour per day: 132W/24h	15 ind/outd	
Freezer 220 litters Whirlpool A-type	225 Wh approx. 610W/24h	10 ind./outd	

TABLE III. MIDDLE PRIORITY LOAD NODES

Load Type	*Estimated distance (m)*	Number of node
Light on kitchen (24W)	10 ind. / outd.	1
Light on room (24W)	10 ind. /outd.	
Washing machine. Fagor Bitermica 1200heat/450 motor / 750 spin dry, approx 750W x cleaning x2 cleaning per week 1500W/7days = 214W/24 h	10 ind. /outd.	1
Tumble dryer Bauknecht 2.200E/1200W. Depending on program (used not very oftem 1-2 days at month 1hour = 40W/24h)	10 ind. /outd.	1
Vacuum Cleaner. Karcher 1.200w. ½ per day = 600W/24h.	10 ind. /outd.	1
Air Conditioning: Convair. High Efficiency 3 devices x 86W = 258 W/h x 10 hours = 2.580x/24h. Only used 2-3months per year	10 ind. /outd.	1
Water pump ESPA well 1000W/h x 1 hour per week / 7 days = 142 w/24 hours	40 ind. / outd.	1
Water pump ESPA aquiferous 750W x 1 hour per week / 7 days = 107w/24 hours	40 ind. / outd.	1
Computer iMAC 125W x 3 hours approx. 379 w/24h	10 ind. / outd.	1

TABLE IV. LOW PRIORITY LOAD NODES

Load Type	*Estimated distance (m)*	*Number of nodes*
Entrance light (24W) Studio light (35W)	15 m (outd.) 40 intd. / outd.	1
Exterior lights (22W)	40 intd. / outd.	1

TABLE V. MOBILE LOAD NODES

Load Type	*Estimated distance (m)*	*Number of nodes*
Microwave Teka: 1.050/750 W	15 m (ind. / outd.)	1
Bread Toaster: Tefal 1.050W	15 m (ind. / outd.)	
Iron UFESA: 1.200W	15 m (ind. / outd.)	
Scanner EPSON 19,2 W/h	15 m (ind. / outd.)	1
Printer Epson: 44W/h	15 m (ind. / outd.)	
Fax Cannon: 66W	15 m (ind. / outd.)	
Sony Trinitron TV: 65W	15 m (ind. / outd.)	1
Power Audio amplifier 10,4W	15 m (ind. / outd.)	
DVD LG: 12W	15 m (ind. / outd.)	
New devices nodes: (4)	15 m (ind. / outd.)	4

C. *Power Sources*

Regarding power generation, there are 2 photovoltaic units 1kW each. One (PV01) operates as a "*grid-froming*" unit which includes a battery rack and the other (PV02) is connected by on-grid inverter, small wind turbine of 2kW connected on-grid, a biodiesel micro CHP of 15 KVA (build up by ourselves) and a rack of batteries.

An important feature of the photovoltaic units is that are installed on a single-axis tracker, the FSA system a world-wide patented technology [24] developed in Mas Roig in lasts 90's (see Figs. 4 and 5). Tracking system in microgrids projects are extremely important to maximize energy production per day, but also to get the maximum power more hours per day and to reduce the storage needs (see Fig. 6). Besides the single-axis tracking, FSA System includes other innovations such as a passive cooling process of the PV field, and a minimize energy losses due to all the power electronics and batteries are inside the prism. The whole unit becomes a plug'n'play device ready to interconnect in an easy and cheap way.

D. *Power Electronics and Configuration*

The power network is enabled by a SMA technology to interconnect the PV units and the micro CHP. However, for the windmill another technology (in this case from *Carlo Gavazzi*) is used. The goal is to test how different technologies could work in the same microgrid.

Fig. 4. Photograph of two FSA units installed at Mas Roig.

Fig. 5. Detail of the interior view of an FSA, including a set of batteries and its charger.

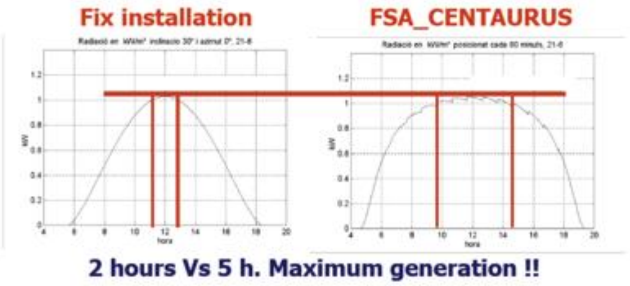


Fig. 6. Comparison between the PV generation of a fixed installation and the FSA.

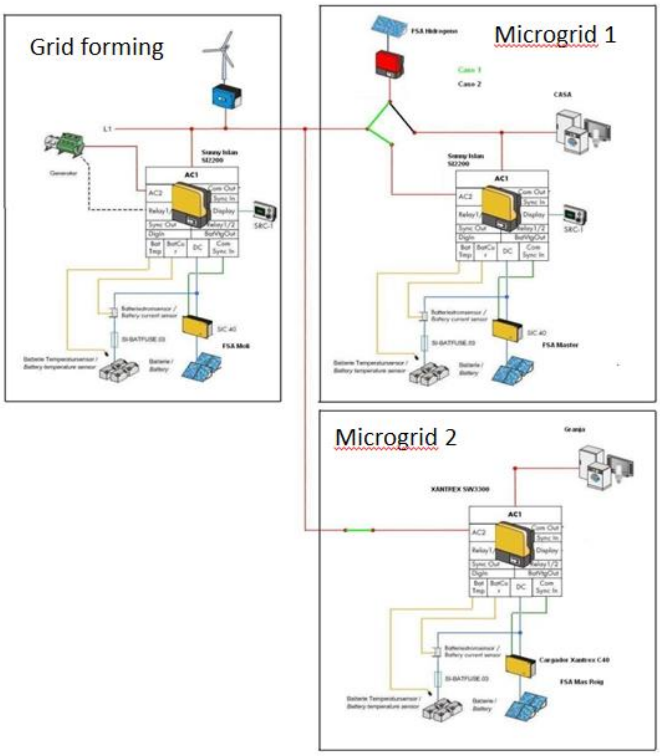


Fig. 7. Multi-microgrid installation at Mas Roig.

E. *Network Configuration*

All of the elements of the microgrid are interconnected in a flexible way to allow two different operational scenarios (see Fig. 7):

- Two microgrids that exchange energy among them;
- One single (and bigger) microgrid with grid emulator.

F. *IT System - Hardware*

The IT system is based on intelligent sockets to control the loads. These elements are able to measure the electrical parameters of the loads and switch on/off according to the orders coming from the central computer. The communication among the computer and the sockets is done by ZigBee protocol. Some real measurements that were made are summarized as shown in Table VI.

nodeMeasurements

Id	Node	day	V	I	Re-lay	S	Q	freq
9588	13	30/09/2010 13:36:56	220.88	0	0	0	0	50
9589	14	30/09/2010 13:36:57	220.68	0.41	1	90.24	0.04	50
9590	15	30/09/2010 13:36:58	221.02	0.41	1	88.93	0.04	50
9591	16	30/09/2010 13:36:58	220.78	0.11	1	21.97	0.01	50
9592	17	30/09/2010 13:37:01	221.06	0	0	0	0	50

G. *IT System - Software*

Software is composed by two different elements. From one side, the expert system that applies the algorithms designed to optimize the microgrid operation. Besides, there is software to set up the project and to motorize the main parameters. Figs. 8 and 9 show different screen shoots of the *NOBADIS*' software.

Fig. 8. Detail of the data acquisition of NOBADIS.

Fig. 9. Detail of the load demand management of NOBADIS.

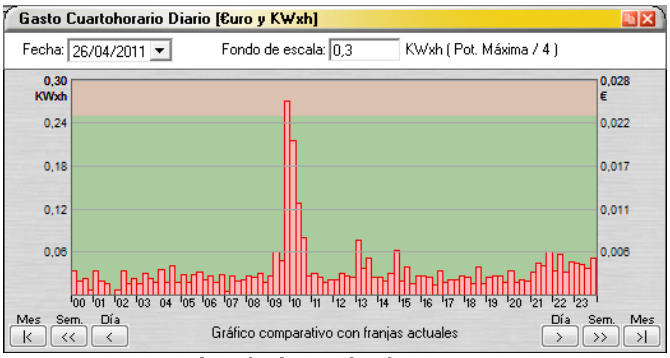


Fig. 10. Consumption along the day April 26th, 2011.

H. *Demand - Power matching*

As it is shown in Fig. 10, the loads in Mas Roig follows a typical curve characterized by two different areas. One is based in "low density loads" that means a certain power value during the vast majority of time (in the example, more than 90%). In parallel, "high density loads" use more energy than the average (e.g. 4 times) but in a short period of time.

This consumption profile is typical of residential houses and commercial and industrial activities. The hypothesis of NOBADIS conception states that is neither optimal to cover high density loads with low density power sources, nor the vice-versa. So that, the matching among the demand and the power generation is enough flexible to adapt automatically high density and low density loads to high and low density power sources, respectively.

V. Communications Infrastructure

The different elements into the infrastructure are communicated by means of ZigBee technology, with the inclusion of the so-called ZigBee nodes. The use of the ZigBee implies a great flexibility when adding new elements into the system.

Fig. 11. Wide area view of the Mas Roig Microgrid, Girona, Catalonia,

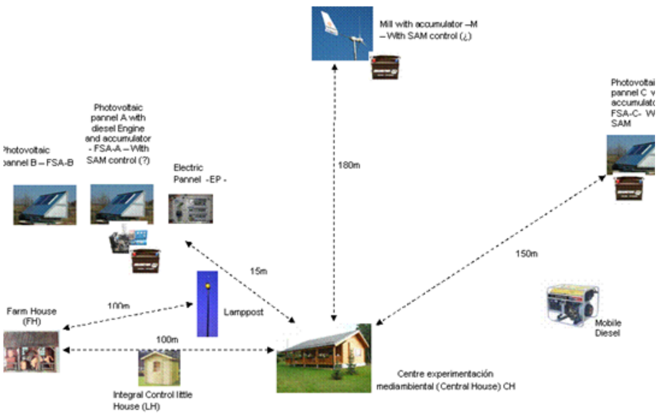


Fig. 12. Communication infrastructure.

Each node is associated to elements and is adapted to its particular needs. The different node types are based on the different loads and generation characteristics, and can be summarized within the following groups:

A. Central Node: this node has an USB connection and is attached directly to the central computer.

RS485 communication: this node provides a communication from the central computer to the device where the ZigBee node is attached and which includes an RS485 port. Through this device, the central computer can read from that device by means of a ModBus protocol (inverters and other appliances).

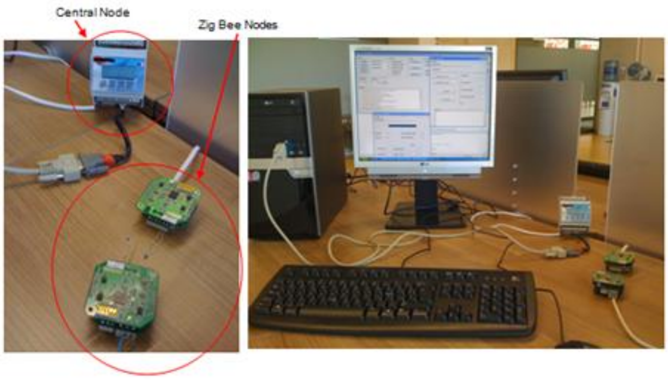


Fig. 13. ZigBee Nodes.

RS232 communication: this node provides a communication from the central computer to the device where the ZigBee node is attached and which includes an RS232 port. With this device, the central computer can read from that device by means of a ModBus protocol.

Control node - Static: this node provides the measurement on V and I on the load attached to the device. It has the capability to measure also to control the switching of a load up to 16 A. This node is always present in the system. Has to be registered and identified.

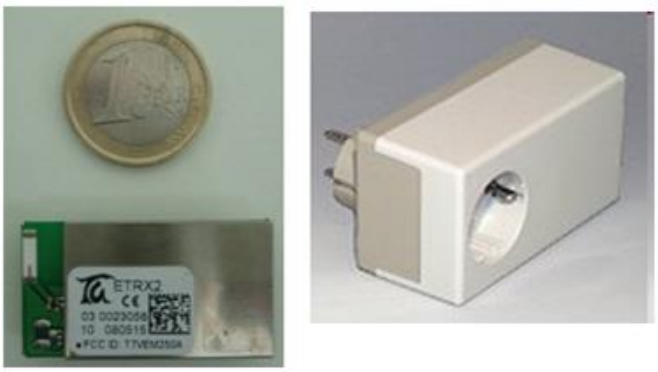
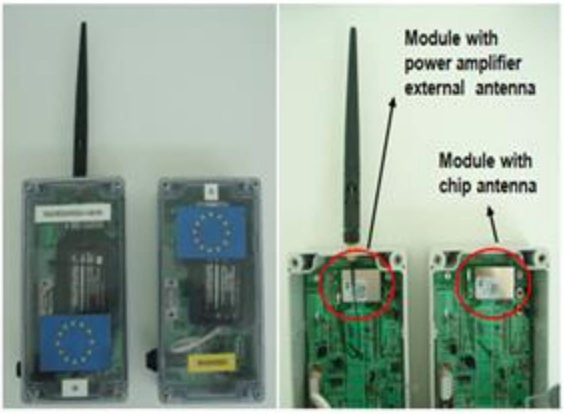


Fig. 14. Static control nodes.

B. Control node - Mobile: this node provides the measurement on V and I on the load attached to the device. It has the capability to measure also to control the switching of a load up to 16 A. Anyway, this node has the capability of appear and disappear into the system (as an example, an Iron, which can be plug in or plug out). When plug in, the device appear into the system automatically. In case of plug out, the node disappears. It doesn't need to be registered before.

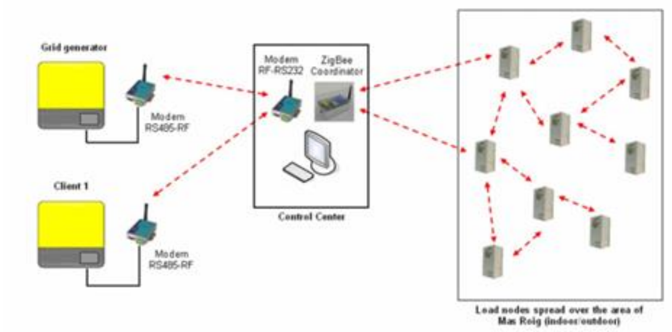


(a)

(b)

Fig. 15. Mobile control nodes.

The selected topology for the Mas-Roig Microgrid is Star type. With this topology, the consumption and delays are the lower as possible, because every element is only active when transmitting and they don't need to send the information packages to each other nodes. The framework technology used for the ZigBee infrastructure is Free-Scale Stack, and the time latency on reading of all nodes will be of 2 seconds, although we will test different sampling rates, due to the fact that the sampling rates has a strong relationship with node consumption, and it is a relevant point for this application.



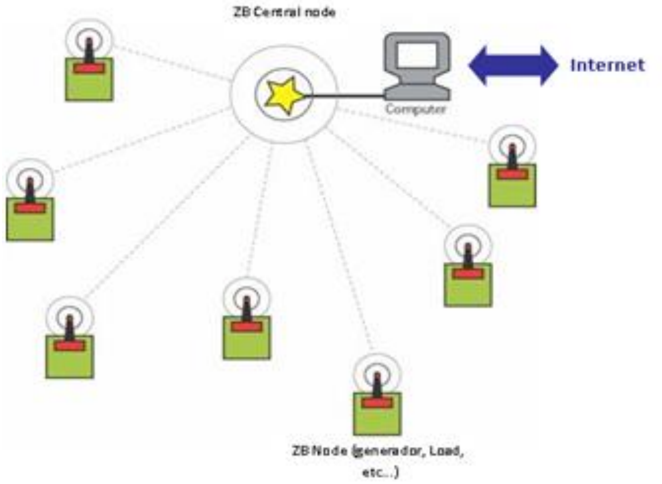


Fig. 16. ZigBee Star Topology

VI. Conclusions

This paper presented the architecture and operation of a rural islanded microgrid. Some lessons learnt are:

- The project is feasible and works correctly in strict islanded operation.
- From a generation point of view is strongly recommended to use only o single power electronics' manufacture in order to avoid operational problems. This is a technical and economical constraint.
- Renewable penetration has been maximized during isolated operation thanks to load shedding.
- Minimizing O&P cost implies minimizing CO_2 emissions, because cost opportunity of not to use renewables trend to be infinite
- There was a black-out in the region (250.000 people up to a week) due to a snow storm (more than 1.500 electric wires were fall down, basically at distribution level). Mas Roig was the only facility which had energy sources. People of surrenders were there to recharge its computers and to keep cool the drugs from the small health facility in the town
- The user must be part of the system. And this is not easy. Maybe one of the mayor barriers to spread these technologies around. It is necessary to go in deep in behaviour science.
- The IT energy cost or EROI (Energy Return Of Investment) must be considered as a critical point. Is not question to get the maximum control technically possible, but the most cost effective in terms of energy consumption.
- Regulatory framework (at least in Spain) do not allow to set up a project like NOBADIS, which shows that to go further with Sustainable Energy Systems is not enough to focus in technology side. Another consequence of this is that there is not interest from private capital to invest in this kind of projects because there is not market opportunity.

VII. ACKNOWLEDGMENTS

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