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Experimental Verification of Hybrid Renewable Systems as Feasible Energy Sources

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Abstract

Renewable energies are a central element in the search for energy sustainability, so they are becoming a substantial component of the energy scenario of every country, both as systems connected to the grid or in stand-alone applications. Feasibility of these renewable energy systems could be necessary not only in their application in isolated areas, but also in systems connected to the grid, in this last case when their contribution reaches a substantial fraction of the total electricity demand. To overcome this reliability problem, hybrid renewable systems could become essential and activities to optimize their design should be addressed, both in the simulation and in the experimental areas. In this paper, a laboratory to simulate and verify the reliability of hybrid renewable systems is presented and its application to the feasibility analysis of multicomponent systems including photovoltaic panels, wind generator and biomass gasification plant, plus energy storage in a battery bank, are described.

Keywords: Renewable energies, hybrid systems, reliability, experimental verification.

1. INTRODUCTION

World energy scenario has been changing in a fast way during the last decades with a substantial increase in energy demand that energy efficiency improvements and energy savings have only been able to alleviate, but not to fully compensate [1]. This is not the only reason for the serious energy problem to be confronted nowadays; in addition, high dependence in fossil fuels, in the order of the 82% at the global level [1], aggravates the situation due to the scarcity of these primary resources and their excessive environmental impact. These two facts: needs for a substantial increase in energy generation and avoidance of a massive dependence on fossil fuels, force to introduce in the energy consumption scheme a big contribution from renewable energies. This high participation is required not only for grid connected applications [2], but also in stand-alone systems [3] where renewable energies can be a solution to the energy needs in not interconnected zones that are an important fraction of the total territory in many countries in South America and, especially, in Africa [4].

Conventional renewable energy sources, i.e.: solar photovoltaic, biomass and wind power, have reached a mature level of technical development as to make possible to base on them a progressive substitution of fossil fuels in future energy scenarios. Economic viability of this substitution is more complicated due to the high prices of these technologies, but economy scale reductions, as the production of renewable systems increases and fossil fuel prices go higher, could alleviate this problem [5]. Basically, the remaining major problem for this high penetration of renewable energies is linked to the feasibility of these energy sources, especially in stand-alone applications, but also in grid connected systems when the total contribution of renewable reaches a substantial fraction of the total energy generation. Possible solutions to this feasibility problem include the combination of several renewable sources in a hybrid system or the addition to the system of energy storage, or both together in a more complete system. Strictly speaking, Hybrid Renewable Energy Systems (HRES) are composed by one renewable and one conventional energy source, or more than one renewable source with or without any other conventional energy system. [6,7]. HRES are becoming a useful solution due to the advances in renewable energies technology and its associated power electronics. By combining two or more renewable systems it could be possible to obviate the problem of reliability of each of them and get, in addition, improvements in the total energy efficiency of the system, when compared with the corresponding values of each of the systems separately. In summary, HRES would allow for the remediation of the limitations of renewable energies in terms of fuel flexibility, reliability and economics.

The simplest HRES combines photovoltaic and diesel systems. The main advantage is the high reliability guaranteed by the presence of the diesel system that can provide the needed electricity when the solar system for any reason (lack of solar radiation, failure in the system, etc.) fails to provide it [8]. Nevertheless, this kind of HRES has two main drawbacks: its environmental impact, due to the emissions coming from the use of fossil fuel, and, when applied to very isolated areas, a low economic viability due to the high cost of the diesel supply to these areas. To reduce the dependence on the diesel system, energy storage can be added to the HRES, accumulating the electricity exceeds in batteries [9]. Diesel dependence can be fully obviated by combining photovoltaic system with other renewable sources, such as biomass or wind systems [10]. In all these configurations storage can be also included, either in batteries or by generation of hydrogen to be used later by fuel cell to generate electricity when needed [11,12].

Given the potential of HRES, many studies have been completed to simulate and optimize their design [13, 14, 15,16], but before the construction of such kind of systems an experimental verification of their capabilities at the minimum significant power is advisable. With this goal, a laboratory has been designed and built at the Institute for Energy Engineering of the Universitat Politècnica de Valencia, Spain, that allows for the assembly of HRES combining different renewable sources: photovoltaic, wind, biomass and hydrogen fuel cells, all of them interconnected by a controlled microgrid that supplies to a preprogrammed load to verify the capability of the selected HRES to satisfy different demand curves with high reliability. Additionally, the laboratory includes the capability to store energy, both in batteries and hydrogen, to cover most of the possible HRES configurations. This laboratory enables to prove experimentally the feasibility in the short and long term of different hybrid configurations, by combining adequately the renewable sources available at the plant, to satisfy any particular electricity demand, which can be defined by a programmable load. All the systems and the programmable loads are working in the 10 kW range.

In this paper the above mentioned HRES laboratory, Laboratory of Distributed Energy Resources (LABDER), is described and the results of its application to the characterization and reliability analysis of a HRES composed by PV panels, biomass gasifier and storage in a battery bank are presented. A second HRES, that add to the previous one a wind generator, has been also operated at LabDER, and its feasibility behavior is presented and discussed. The choice of the two first HRES to be experimentally studied in LabDER is justified by the fact that these systems are the most cited in the simulation and optimization studies published so far, especially in applications to cover residential needs in non-connected areas.

2. LABDER DESCRIPTION

Block diagram of the laboratory is displayed at figure 1 and brief descriptions of each of its components are included in the next paragraphs.

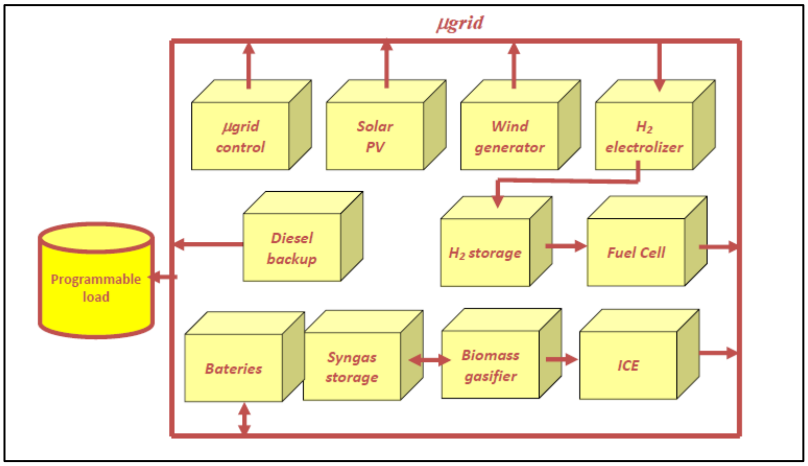

Figure 1: Block diagram of LABDER system

a) Photovoltaic system

The LABDER photovoltaic generator is made up of monocrystalline and polycrystalline silicon modules mounted on the roof of the laboratory, facing south with tilt angle of 30º to produce maximum annual energy. The total power of the photovoltaic generator now installed is 2.1 kWp, and the panels are connected to a single phase grid inverter. The system is being expanded up to 9 kW, three phases system by adding additional modules and two new single phase inverters.

The solar radiation in the photovoltaic generator and the modules temperature are measured using a Datasol Met computer system. The operating point of the panels and the inverter, currents, voltages, power and energy injected to the grid are also monitored. This information allows to the management system to check the correct operation of the system and to know the energy produced at any time.

b) Wind energy system

Electricity generation from wind energy is obtained in LABDER by a aerogenerator with 5 kW peak power and 3 kW for winds with a 12 m.s^{-1} speed (figure 2). Located at the top of a 16 m. tower, this system is composed by a three pales 3,5 meters diameter wind turbine with an electrical machine connected to the turbine axis. This electrical machine, optimized for the available power of the turbine, is a synchronous one with the excitation provided by permanents magnets.

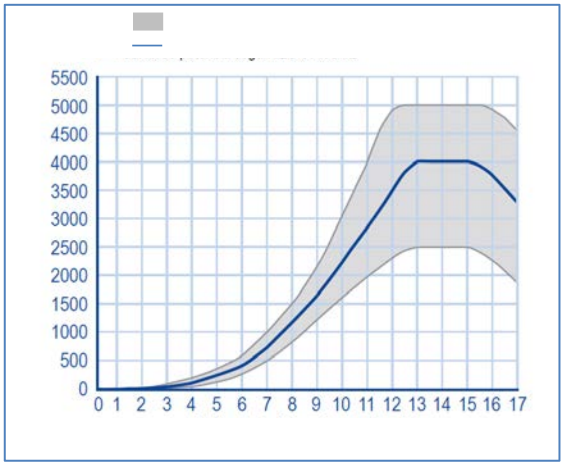

Figure 2: Power dependence on wind speed.

The system includes a rectifier and inverter devices, with a 3,2 kW power and input voltages in the range 350 to 500 V, that matches the output of the wind system to the microgrid frequency, and a dumping load to receive that fraction of the generated electricity that the microgrid cannot absorb.

c) Biomass system

Biomass energy in LABDER is provided by a biomass gasification plant. The gasifier with a consumption of 13 kg/h of biomass (with 10% of moisture) produces about 30 Nm^3/h of syngas that, when burnt in a gas internal combustion engine, provides a maximum electricity power of 10 kWe. Table 1 shows the main features of biomass gasification power plant.

Biomass gasification reactor type	Bubbling fluidized bed
Biomass reactor dimensions	Diameter: 106 mm, Height: 155 mm
Fuel type	Wood chips (10 – 15 mm maximum length) Pellets (diameter 6 mm, 15-25 mm length)
Biomass hopper capacity	237 l (up to 166 kg of biomass)
Biomass input (@ 10% moisture)	6 - 13 kg/h
	30 - 60 kWt (referred to Higher Heating value. HHV)
Syngas production	13 - 33 Nm^3/h
Syngas Higher Heating Value	5 - 5,8 MJ/Nm^3
Total Efficiency (generated electricity to biomass input ratio (HHV)).	15 – 20%
Power generation engine	cylinder capacity 1.8 liter engine velocity 1500 rpm compression ratio 8.5:1 Maximum Power 10 kW [220/240 V & 50 Hz]

Table 1: Main features of biomass gasification power plant

d) Hydrogen system

Hydrogen system is composed by an electrolyzer and a PEM fuel cell, both of them connected to the microgrid. (Figure 3)

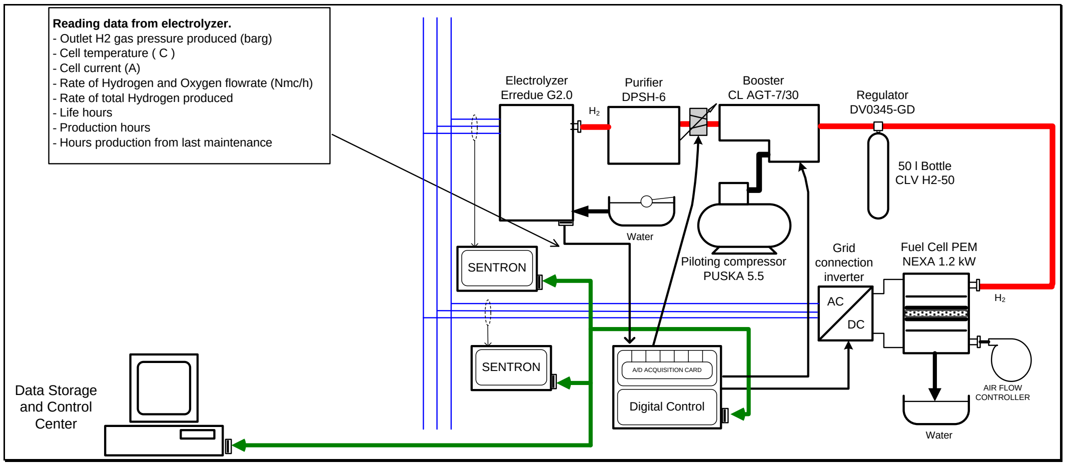

Figure 3: LABDER Hydrogen system

Fuel cell is the well-known Nexa 1200 model from Ballard. Maximum output DC power is 1200 W. Output voltage range is 22 V to 50 V and corresponding current range is 49 A to 1 A. Both output voltage and current are DC values. In order to inject the necessary current into the grid, a grid connected power inverter is used. This converter is managed by the digital control, which fixes the corresponding current with the power that should be compensated

Hydrogen production is done by means of an alkaline electrolyzer, with a nominal power of 7,2 kW, using distilled and deionized water. Products of electrolysis are hydrogen and oxygen. Currently, oxygen is not used, but in the future it will be used to increase the efficiency of syngas production in the biomass power plant. Hydrogen is pipelined to a purifying system which can increase its purity up to the value requires by the PEM fuel cell (99.995%). Purification is made by extracting residual oxygen, humidity and electrolytic solution from the hydrogen flow. Purifying system is based on a Pressure Swing Adsorption process. It consists of three filters (activated carbon, aluminum oxide and hygroscopic salts), and requires a minimum of 6 bar of compressed air flow supplied by an additional compressor. The generated hydrogen is stored in a 50 liter gas bottle up to 200 bar pressure. Nominal hydrogen production is 1.33 Nm^3/h at 2.5 bar of outlet pressure. The entire electrolysis process is controlled by a Programmable Logic Controller (PLC), with a serial port that makes it possible to consult all these parameters from an external device by means of a RS232 serial communication with Modbus RTU protocol.

e) Storage systems

Looking for feasibility of HRES in isolated applications, storage systems could play an essential role. To prove this potential in specific configurations, LABDER includes two different storage systems: batteries and hydrogen. Hydrogen system has been explained in the previous paragraph. The battery bank of LABDER is composed for 4 batteries ENERSOL 250 connected in series working at 12 V and 250 Ah each. The whole battery bank work at 48V and the maximum storage capacity of the batteries is close to 12 kWh However, to avoid a discharge level of the batteries below 50%, the maximum available stored energy from the bank is 6 kWh.

A storage system for the syngas generated by the biomass gasification plant is under consideration to prove its potential and technical and economic viability in this type of applications.

f) Microgrid control system and data acquisition system

Two main systems have been developed for LABDER management: a microgrid control system (MCS) and a data acquisition system (DAS). The MCS is devoted to control the operation of all microgrid systems and it is developed as a distributed control, where the application packages for communicating with the distributed intelligent processors reside in a control server and update the relational databases in real time. The control server also acts as a file server host, where the graphical information (screens design, images, etc.) are stored. End user work station represents the graphical link between the server and the operator of the microgrid. DAS system is based on the storage of all distributed intelligent processors data, via communication cards, in a common database and processed thereafter. This database is operated by a graphical SCADA, developed using Labview, to provide the requested information to the energy operators in an easy-to-use format. The main components to perform the control of the microgrid are a PLC (to control various contactors to connect and disconnect the renewable sources (solar panels, wind turbine, generator, etc.), and a hybrid inverter (HI). The HI sets up the operating modes of the micro grid: grid-tied, insulated, generator support, battery support, batteries charging, load supply and energy sales. The HI can work in grid-tied mode, to inject energy into the grid from batteries or renewable resources or in insulated mode where creates an electrical network from a DC power source and use the renewable resources to charge the batteries. To manage the energy flows, the control system gets information from the HI, PLC and existing power meters. All data is stored in the database located in the server.

Control system for LABDER is displayed at figure 4. Hardware for the communication net uses Modbus TCP/IP protocol; to achieve it, all data sources are transduced from original protocol to MB TCP/IP; figure 5 shows the basic scheme of installation: communication path starts in data source device (inverter, sensor, or power analyzer) and follows to specific transducer (RS-232, RS-485 and others to TCP/IP), to the network switch and finally to a PC.

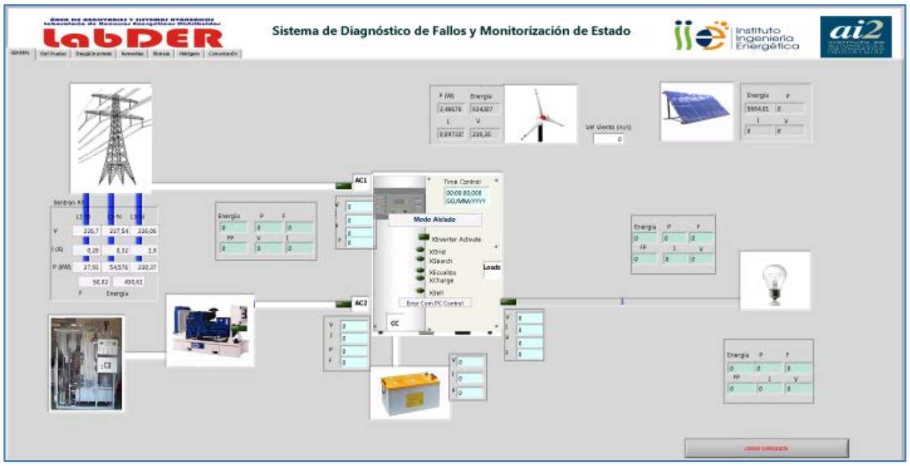

Figure 4: User interface of the LABDER main supervisor system,

All supervisory software has been developed using a LabVIEW environment. Program code is split in modules which performing tasks such as: Supervisor, Communications, Save data and Virtual Server. All device registers and its times are posts in a virtual server which acts as slave for another PC in the same net. This makes possible to share information on line with the main control system.

Related to condition monitoring and fault diagnosis, each renewable energy source has different treatment; also, using LabVIEW environment have been created interconnected program blocks representing the components of each group generating; after that, was carried out the following activities: simulation and calculation of standard deviations, model fitting, definition and development trend analysis and refinement of fault trees.

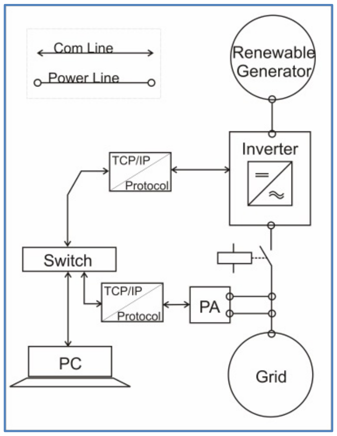

Figure 5: Basic installation for each renewable generator

First experiments in LABDER have been oriented to test the capabilities of the facility to replicate HRES systems in the range of a few kW and check their response in a feasible way to different demand curves.

3. HRES FEASIBILITY STUDIES AT LABDER

Two different hybrid systems, those that appear more often in the published studies for non-connected areas, have been assembled in LabDER to experimentally check their feasibility in the supply of electricity to those areas. The first system tested (HRES1) was a combination of photovoltaic panels, biomass gasification and a battery bank. The second one (HRES2) adds to that configuration a wind generator. Both systems were controlled to supply a typical demand curve in the residential sector with two main peaks in the morning and in the evening, respectively. To facilitate the experiments, the demand curve was compressed to 3 hours duration in the preprogrammed load, considering this time was long enough to check the capabilities of the systems to fulfill the energy requirements.

3.1 HRES1 study

Many studies have been published [17, and references there in] on the potential of hybrid systems based on PV, battery banks and in some cases energy storage in battery banks, but very few include experimental verification of the system behavior [18, 19, 20]. To address this study the HRES1 was assembled at LabDER.

Total power generated by the hybrid system can be expressed by the addition of the contributions from each of the renewable sources:

$$P_{gen}(t) = \sum_i c_i(t) * P_i(t)$$

where $P_i(t)$ represents the nominal power of each renewable source and $c_i(t)$ the contribution at each moment of that source to the total generated power .

Figure 6 shows the total power generated to cover the demand profile by adding the contribution of the solar panels, the biomass gasifier and the batteries.

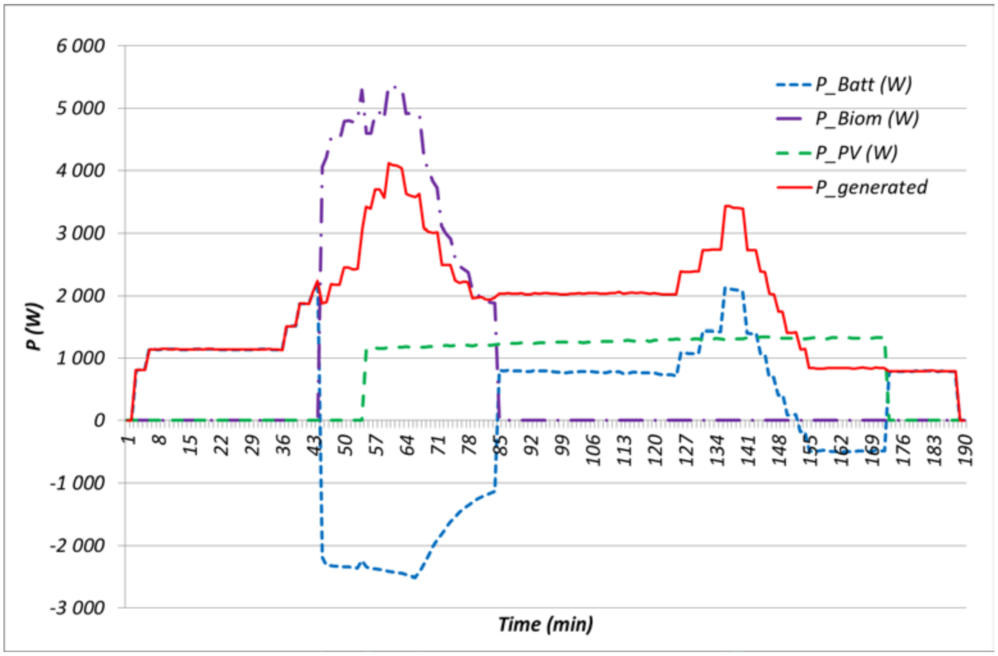

Figure 6: Total generated power and contributions from each element in HRES1

As it may be observed in the plot, at the beginning of the experiment, in the absence of solar radiation and with full charged storage bank, the demand is met with the electricity stored in the batteries. When the charging level of the battery bank decreases down to 50%, biomass gasifier starts the generation, covering the demand and recharging the storage bank. Later, PV energy starts but the gasification plant continues running until battery storage is again full charged, which allows beginning the next cycle of operation under the same conditions of the previous one.

Negative power in the case of batteries indicates that batteries, at that time, are in a charge process taking energy either from the biomass gasifier, in the first part of the discharge, or from the photovoltaic system, during the final part of the discharge. Control system was setup to change to battery charge status when the bank is below 50% of its nominal full charge. The normal solar radiation profile in the experiment was almost constant due to experiment was made around noon. Sunset and sundown were substituted by an on-off control of the PV energy input to the system.

Figure 7 plots the contributions of each of the elements of the HRES1 to the total generated power. PV panels contributed with around 60% of their nominal power, while biomass gasifier contribution is slightly smaller, in the order of 50%, and battery bank is just working at 20%. So, the system has enough power to supply any extra power demand that could appear.

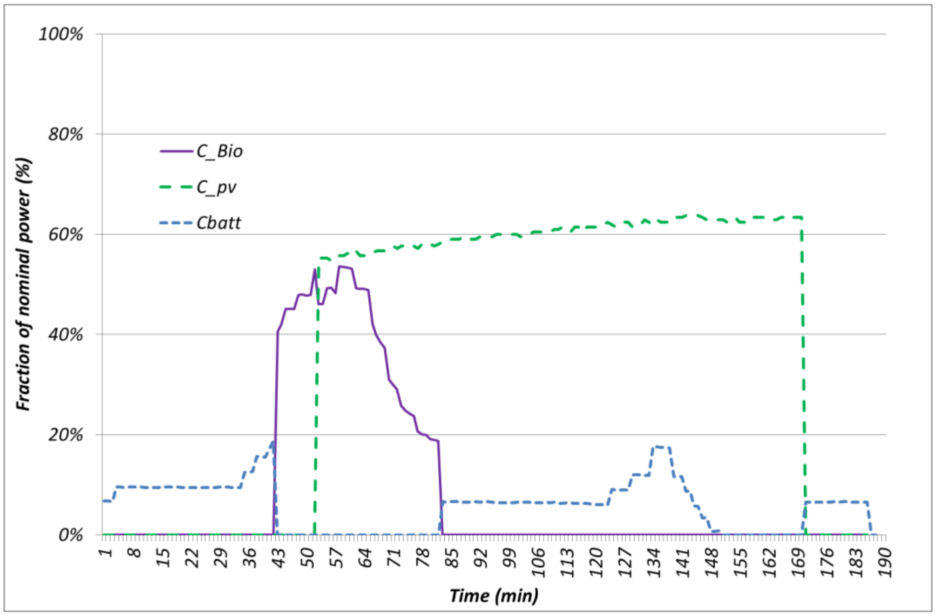

Figure 7: Contributions from the different HRES1 elements to the generated power.

By comparison of the generated power and the power transmitted to the load is possible to deduce the losses in the system.

$$P_{loss}(t) = P_{gen}(t) - P_{load}(t)$$

and the fraction they represent:

$$f_{loss}(t) = {}^{P_{loss}(t)}\big/_{P_{gen}}\,(t)$$

These losses are shown at figure 9, both in absolute and percentage values.

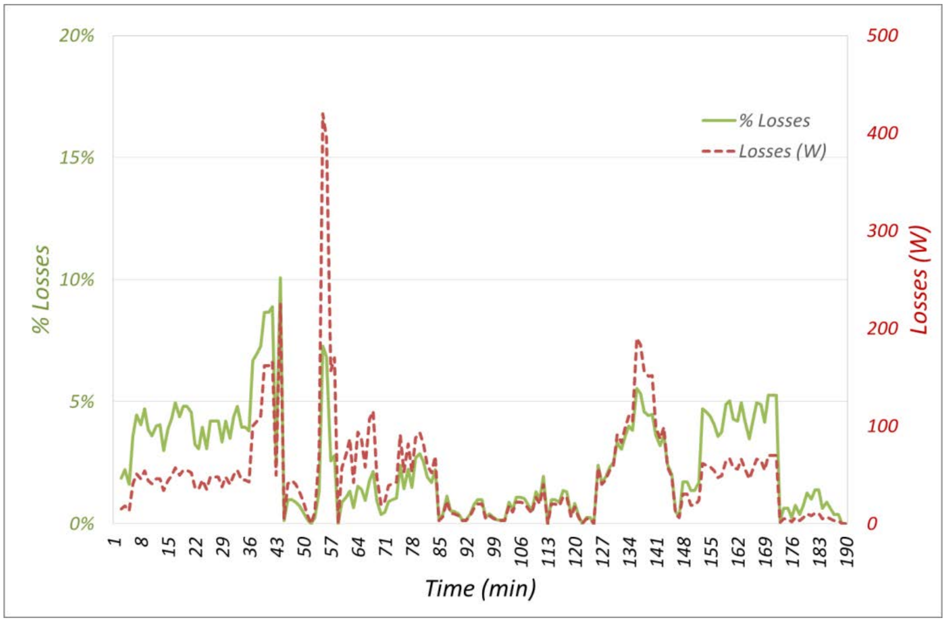

Figure 8: Losses in the HRES1

Results indicate that losses are small, 3% on average , and by comparison with figure 7, that shows which source is the dominant one at each time, it can be deduced that main losses appear when battery bank is the dominant source or sink, reaching values at that moment in the range 5-10%.

Finally, the quality of the electric power generated by the HRES1 has been monitored by measuring the voltage and frequency of the transmitted power to the load. Figure 9 summarize the results. In the absence of the gasification system, the fluctuation level is almost zero. When the gasifier starts to operate, its associated syngas engine introduces, due to its less stable behaviour, some fluctuation level, in the order of 4%, for both, voltage and frequency, of the output power as detailed at figure 10.

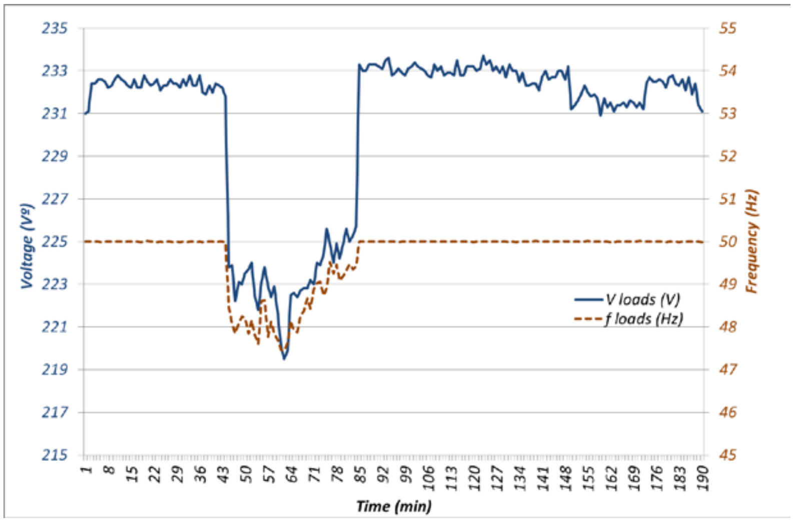

Figure 9: Voltage and frequency of the HRES1 delivered power to the load.

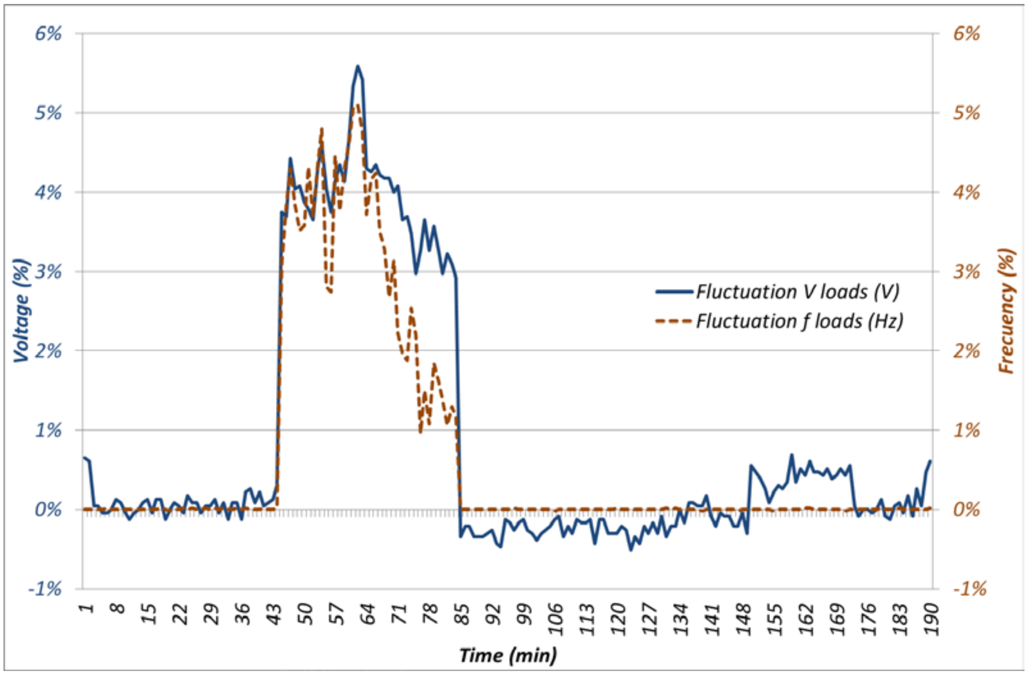

Figure 10: Fluctuation levels for voltage and frequency of the HRES1 power output

In summary, it could be concluded that the assembled HRES,including PV panels, biomass gasifier and storage in a battery bank seems to be able to cover the residential electricity demand profile in a flexible and reliable way with a very low level of losses. The substitution of a diesel generator backup by a biomass gasifier does not introduce any degradation in the system feasibility, by the contrary is very similar to the values obtained for hybrid systems with diesel backup [18], with the advantage to avoid the use of any fossil fuel. The storage of energy surplus in the battery bank guarantees the effective utilization of all the available renewable energy and the possibility to reduce the nominal power requirement of each of the renewable sources in the system what is in accordance with previous studies for this kind of systems [19,20].

3.2 HRES2 study

Many studies includes a wind generator in HRES specially in applications to non-connected areas [21,22] but very few have experimental results for the proposed systems [23]. To address this topic a second hybrid system (HRES2) was assembled in LABDER. In this new system (HRES2), in addition to the PV and the biomass gasification plants, the wind generator was included.

A similar behavior to the previous system in its capability to supply the demand curve was observed, as detailed by the data plotted at figure 11.

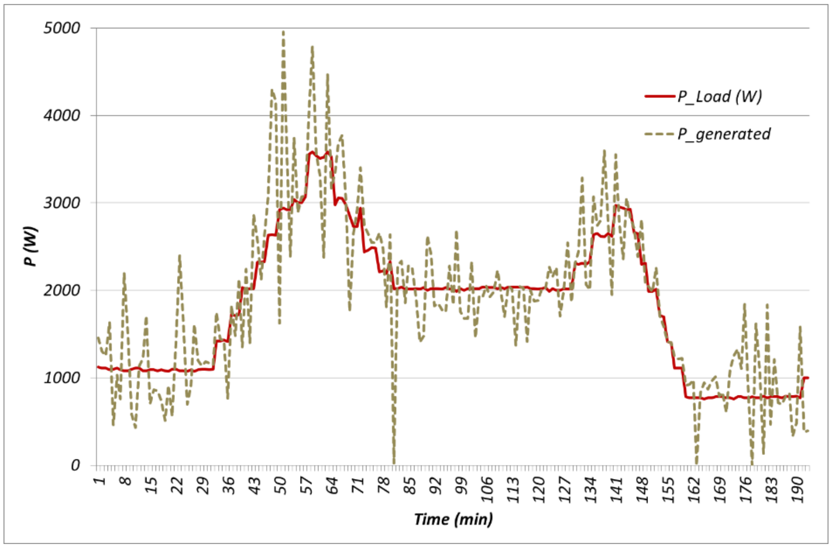

Figure 11: Power generated and transferred to the load by the HRES2

The main problem with this configuration is the high level of fluctuations in the power production from the wind generator, which was filtered by the battery bank and the gasifier, as can be deduced from figure 12, where contribution of each component of the HRES2 system is detailed. The power transmitted to the load did not present these fluctuations

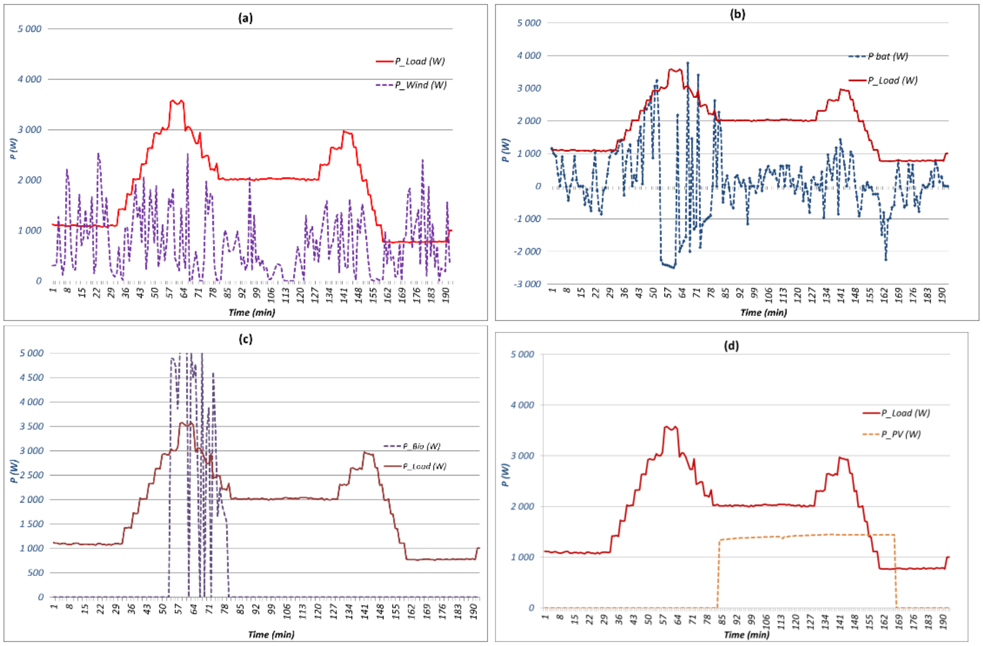

Figure 12: Contribution of each energy source to the power output in HRES2

(a: wind generator, b: battery bank, c: biomass gasifier, d: PV panels)

Studies are now in progress to eliminate the fluctuations in the wind generator in order to avoid any deleterious effect on the lifetime of the battery bank and the gasifier.

Apart from this fact, the system is able to cover the demand curve with the same level of reliability than the previous one, as shown at figure 13.

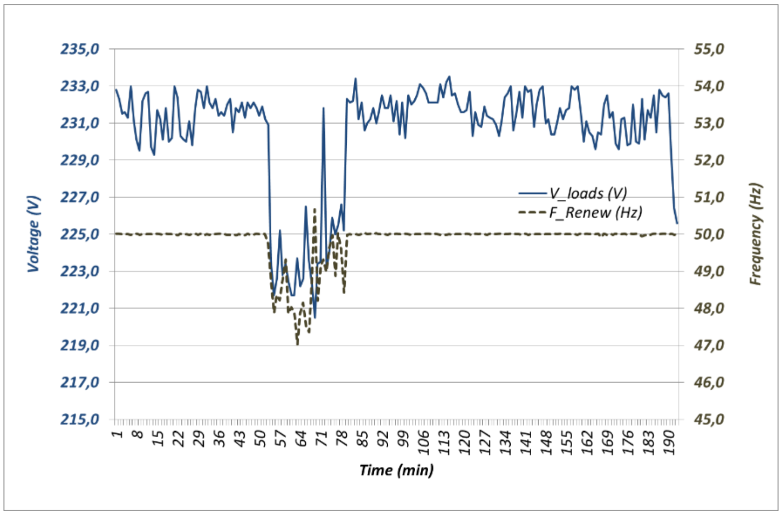

Figure 13: Voltage and frequency of the HRES2 delivered power to the load.

In summary, the inclusion of the wind generator in the HRES with a nominal power similar to the power of the other renewable systems does not deteriorate the feasibility of the system. Nevertheless the high level of fluctuations in the wind power forces to the battery bank and the biomass gasifier to compensate them in order to get an smoothed output power. This effect has not been detected in other experiments with a similar system [23] probably due to the lower percentage of the wind power contribution to the output power in those experiments.

CONCLUSIONS

In conclusion, given the need for a substantial increase in the participation of the renewable energies in a sustainable scenario oriented to cover energy needs, both in connected and isolated systems, it is important to assure the feasibility of these energy sources. To reach this feasibility goal, hybrid renewable energy systems, either alone or with energy storage, are a promising solution that has been proposed by many authors, but are still in a preliminary phase of application. Experimental verification of the potential of any particular renewable hybrid systems would require a preliminary test of its capabilities at the minimum meaningful power level. LABDER laboratory has been defined and constructed with this idea in mind and it now in operation. Application of this laboratory to the study of the feasibility of two specific hybrid systems for the standard demand curve of residential segment has proved the versatility of the laboratory for this checking process of hybrid renewable systems and the adequate response of those two hybrid systems for the considered application.

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