Optimization of a hybrid renewable system for high feasibility application in non-connected zones

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Abstract

Renewable systems are especially suited for electricity generation in remote areas but, where high reliability of the electricity supply is required, a hybrid system including electricity storage could be the only solution to avoid the lack of feasibility in single renewable systems. In this paper a hybrid system composed by photovoltaic panels, a biomass gasifier and a battery bank is presented. The system was designed and constructed at the Distributed Energy Resources Laboratory (LabDER) in order to supply electricity to a laboratory complex in the Institut Supérieur des Techniques Appliquées, Democratic Republic of Congo (ISTA-DRC). System behavior was also tested in LabDER prior being installed and operated in the final place. Design characteristics and commissioning results are presented together with the experimental verification of the capability to fulfill the demand with very low fluctuations in the generated electricity supply.

Keywords: *Renewable energy, hybrid systems, reliable supply.*

1. Introduction

Democratic Republic of Congo (DRC) has an extraordinary potential for renewable energy generation, mainly hydro. It is estimated that the use of these resources could produce 100 GW of electrical power, 40 of them at one point, Inga [1]. Despite this, only 11% of the population in DRC has electricity access at home [2]. In addition, transport and distribution electricity network is out of date and unable to support current consumption, which results in constant power outages. In the places where electricity is essential, such as hospitals, hotels, public buildings, etc., the problem is circumvented by using fossil fuel generators to get some security in electricity supply. However, remote areas simply do not have electricity.

Despite it has been deeply demonstrated that electricity is necessary for the development of any community, in the case of remote and isolated communities, electricity supply is still a challenge [1]. Responding to this need, renewable energy systems (RES) may safely generate electricity for minimum demand requirements without implementing large facilities or networks by using robust systems integrated in microgrids that leverage generally abundant renewable resources in the communities in which it has to be developed the project.

As a result, hybrid renewable energy systems (HRES) are becoming more popular worldwide mainly for rural power supply. Compared to internal combustion generator systems (ICG), HREs are eco-friendly and economic, particularly when rural areas don’t have easy access to fuel supply and it is brought from main cities, thus increasing the cost and environmental price of energizing [3, 4]. Many previous studies on HRES are based on analyzing the specific energy needs of a geographical area and identifying the optimized energy solutions based on HRES configurations. [5] Studies carried out in rural communities demonstrate the benefits on installing HRES, as a means for reducing the dependency to fuel price fluctuations, overcoming the limitations in the electrical grid expansion of major networks, and enhancing the use of local resources, which don´t depend on external sources and promote the sustainability of the projects [3, 6, 7].

Other research works are focused on implementing optimization algorithms to define the convenient HRES configuration when various objective functions are considered, such as levelized energy cost, unmet demand ratio or fuel consumption [8, 9, 10]. They are based on multi-objective and multi-criteria optimization approach, such as Pareto analysis and weighed sum or probabilistic, iterative and heuristic methods [11]. Dufo-López et al. [12] was one of the firs published research works introducing the concept of multi-criteria optimization to optimize HRES, considering the life cycle cost of the system as objective functions. Thereafter, published works have been including different objectives in the design, such as power supply reliability [8,13], pollutant emission [14], utilization of renewable energy potential [15], or the importance of identifying techno-economical parameters to represent the local context [16].

Latest studies have also incorporated into de analysis demand side management, combining HRES generation with demand response strategies, aiming for reduce the gap between the intermittency energy generation of renewables and the energy requirements. These approaches utilize demand response resources for the energy management of a micro-power system supplied by a HRES in order to guarantee the systematic exploitation of local renewable sources with a reliable power production, avoiding the expensive feedstock storage and the uncertainty of public subsidies [17]

Furthermore, this research goes a step forward in the overall evaluation of HRES, including the optimization of the design together with the experimental validation of the system operating at actual conditions. The work is organized in two main stages. On the first one, an economic optimization of the system by means of the micro-power optimization model HOMER Energy was accomplished in order to analyze the different HREs alternatives based on the local context. In this part, a feasibility analysis of the system was performed, operating as isolated system. The hybrid generation system considered was a solar plant, a biomass fixed-bed gasifier which provides syngas for operating the motor generator, a battery bank to create the grid or to serve as basic storage, and an inverter DC/AC for solar power. On the second stage of the research work, the HRES system was built and tested at LabDER prior being sent to its final destination. During the experimental validation, a programmable electrical network manager was also used in order to test the respond of the system to different load profiles. This experimental validation, together with the initial optimization process, is presented in this paper.

The project has been developed by the Institute for Energy Engineering (IIE) in collaboration with ISTA. It aims to supply electricity to a center for studying renewable energies in a two-floors building with a total area of 350 m^2. The building encloses several energy labs, computer center, classrooms, offices and power supply equipment.

HRES alternative presented in this paper corresponds to a robust electricity production systems based on the highly availability resources of solar and biomass. The project involves the use of a solar-biomass generation system to ensure a high feasible electricity supply in remote areas as well as in areas where electricity is vital.

2. Optimization of the Renewable Energy System Configuration

The HRES system configuration was optimized for ISTA local conditions, a renewable laboratory in Kinshasha, DRC. During the process different alternatives were analyzed under constrains of being 100% renewable, so no ICG systems are considered, and a maximum annual capacity shortage of 5% allowed. ISTA´s Renewable Energy System was optimized and modelled in order to study its response to the energy requirements of the ISTA Laboratory center. The objective was to evaluate whether the optimized alternative presented for ISTA is suitable and the building energy needs are met in a reliable and sustainable manner, while analyzing the economic and environmental aspects of it. The study was conducted in several steps, beginning with the estimation of the building´s demand of electricity, to continue with natural resource assessment, analysis of the technologies, evaluating the environmental and economic impact with HOMER software package developed by NREL for designing micro-power systems [18], and the experimental validation of its operation under different load profiles.

a. Description of the Location

Solar-Biomass Generation Plant was installed at ISTA located in Kinshasa, DRC. DRC has the potential to be one of the richest countries on the African continent and a driver for African growth. Total area of DRC is 2,345,409 km^2 [19], enclosing a major river, the Congo River, and a forest area of 154,135 thousand ha. The population in 2013 was 67.51 million, with a 2.58% annual growth rate, being the capital and largest city Kinshasa. 65% of the total population is classified as rural, even though the share of urban households is growing at a fast rate. Regarding agricultural land, DRC has a total of 224,500 km^2, corresponding to 9.9% of total land area, while approximately 45% of DRC’s surface area is covered by primary forest [20].

Furthermore, DRC is located in a very high solar radiation area where values ranged between 3.5 and 6 kWh/m^2. This makes installation of photovoltaic systems viable in many parts of the country, as well as the use of thermal solar systems [21].

Based on this natural potential, Kinshasa was considered a good candidate for the implementation of HRES.

b. Electricity Demand of the ISTA Laboratory Building

The building energy demand, which had to be 100% covered by the ISTA HRES, has been estimated. It is composed by a computer room, a classroom, four professor´s offices and a Renewable Energy Center enclosing a laboratory for biomass characterization and a second laboratory with the hybrid generation system. In order to accurately model the respond of the system to the energy needs, hourly demand is analyzed for the different rooms in the building. Figures 1 and 2 show the daily energy requirements and the load profile for an average month, respectively.

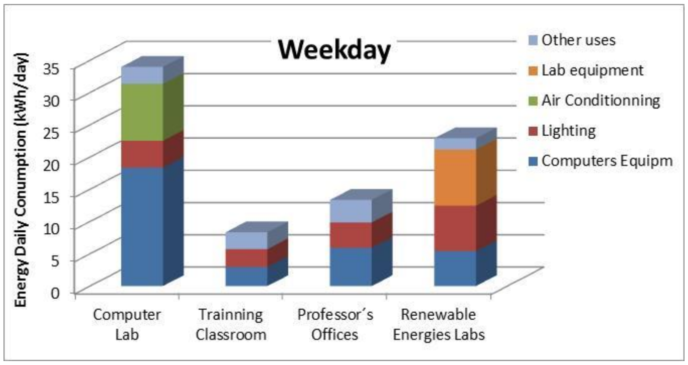

Figure 1. Daily energy needs

Main energy needs are identified during the morning, from 7:00 until 13:00 when lunch break occurs. During the afternoon energy demand decreases, observing a stable demand of 3 to 5 kW from 14:00 to 18:00 hours, mainly due to the use of the Computer and the Renewable Energy Lab (Figure 2). In the evenings, from 19:00 hr to 7:00 hr in the morning, it is required just residual electricity of approximately 1 kW.

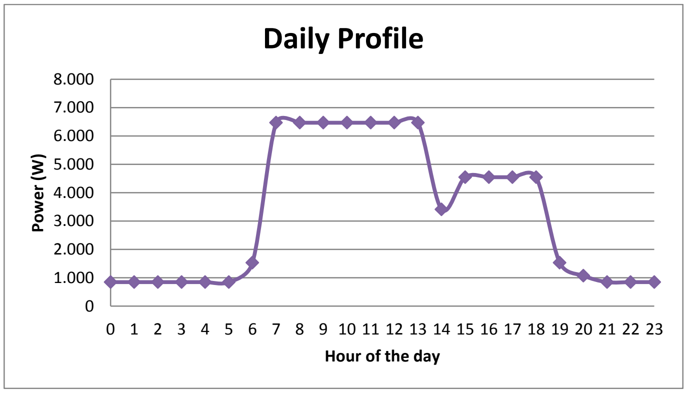

Figure 2. Average daily power demand profile at the ISTA Laboratory Center

Analysis is carry out based on the data gathered at ISTA together with the annual hourly demand forecasted using HOMER Generating Synthetic Load Data [22]. A representation of a complete year is provided in Figure 3, which illustrates the power profile of a typical day per month.

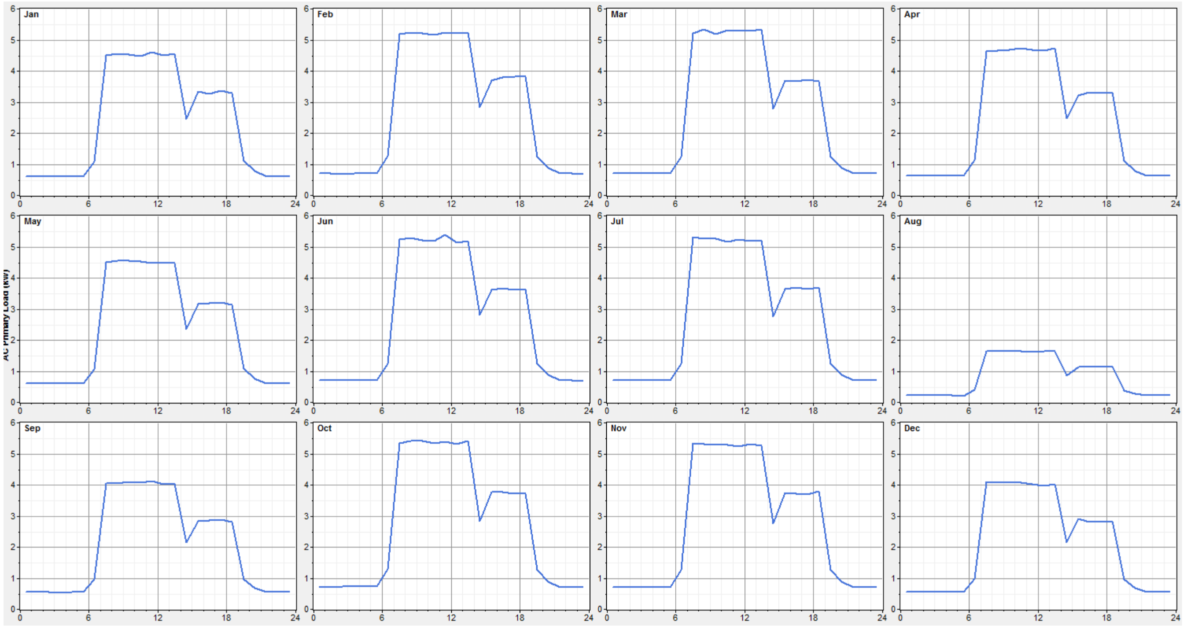

Figure 3. Profile of the average power demand per month

Synthesized data of monthly load profiles shows an annual average power of 3 kW and energy consumption of 56.1 kWh/day. Maximum annual power peaks of 8 kW are registered in February and June with a highest daily energy demand of 61 kWh/day, while August presents the lowest energy requirement with 22 kWh/day and a load peak of 2.5 kW. All these data are summarized in Figure 4.

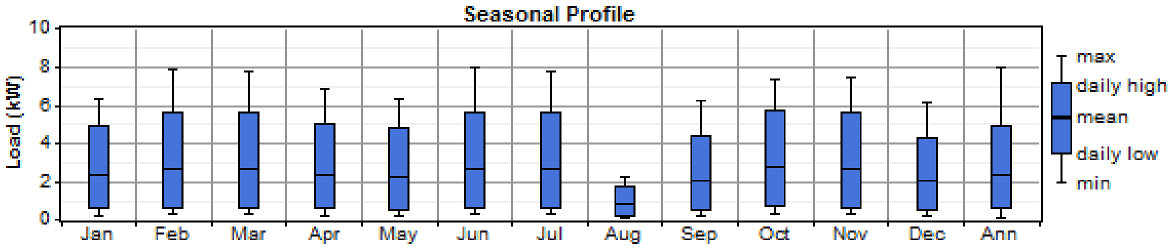

Figure 4. Average power needs per month along the year

c. ***Natural Resources***

Once the demand of the building was estimated, an assessment of the natural resources was necessary to determine the capacity for renewable generation. A pre-feasibility analysis of the renewable potential at the specific location highlighted solar and biomass as major potential sources, therefore further analysis of these resources was performed.
Solar resource was evaluated using the PVGIS-CMSAF [23] solar radiation database at the location of Kinshasa (4°19'54" South, 15°18'50" East, and elevation: 283 m a.s.l.), resulting an annual average of solar radiation as high as 6.4 kWh/m^2/day and a clearness index average approximately of 0.641. Solar radiation was considerable throughout the year (Figure 5), thus significant PV power was expected without any seasonability.

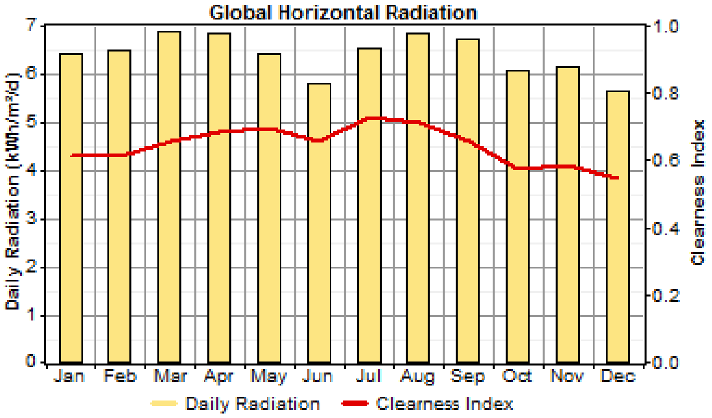

Figure 5. Solar Radiation Profile at the ISTA location

Regarding biomass availability, DRC has 145 million hectares of forest (47% of the total forest resources in Africa) with an annual biomass production of 100 million tons (35% moisture) [24]. It is estimated that DRC consumed 54.7 million tons (74.5 million m^3) of wood for energy use, mainly for domestic energy as firewood and small-scale commercial sectors [25, 26].

Moreover, reducing the demand for firewood is a key factor for reducing deforestation and exhaustion of DRC's natural resources [26,27], so more efficient forms of biomass energy generation need to be implemented and promoted, being gasification a clean alternative. Biomass potential is large, annual forest growing represent an energy equivalency of 28 million of toe (tons of oil equivalent), while agricultural biomass wastes are estimated in 0.48 million of toe and it will probably increase over the time as a consequence of general agricultural progress [28].

Characterization of available biomass was carried out at IIE, where three samples of the most representative species were analyzed, obtaining the results detailed in table 1.

Samples	Moisture, (%bh)	Ashes, (%bs)	Density, (g/cm^3)	Higher Heating Value (HHV), Wet (MJ/kg)	HHV, Dry (MJ/kg)
S_1: FUMA	8.31%	0.6%	0.434	16.14	17.60
S_2: NTOLA	13.25%	0.37%	0.513	16.95	19.54
S_3: LIFAKI	13.57%	2.36%	0.614	15.74	18.21

(%bh)= % of wet base;   (%bs)= % of dry base

Table 1. Characterization of available forest biomass species in DRC

Despite biomass species presented similar characteristics, NTOLA had higher HHV and lower percentage of ashes, being the more convenient for the gasification process.

d. Components

Analysis of RES components were carried out by modeling the electrical generation technologies for solar and biomass sources. Taking into account the expected maximum demand, together with possible increases in a near future, and the need for a reliable supply, the ISTA HRES system (figure 6) was modelled with two generating units: 10 kW solar PV and a 10 kW biomass gasifier, together with a 10 kW battery bank for electricity storage.

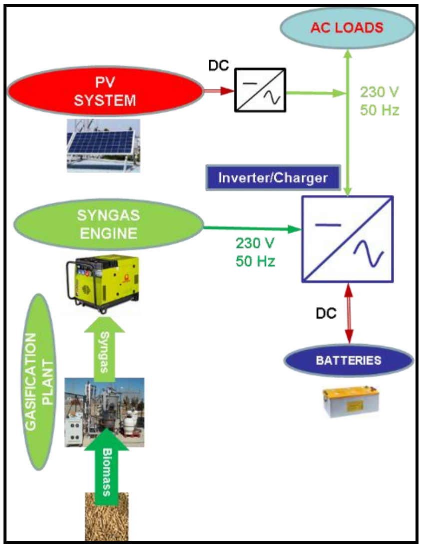

Figure 6: Scheme of the ISTA-HRES.

Solar PV system was composed by panels in series with no tracking system. Panels were configured as fixed tilted with an optimal slope of -7º at the location 4º19’ south (latitude). Estimated losses of the PV system were also considered, such as those related to temperature and low irradiance (12.8%), angular reflectance effects (2.9%), and other losses such as cables, inverter etc. (14.0%). In overall terms, combined PV system losses were estimated as 27%. Economic modelling included capital and replacement cost as well as the annual operation and maintenance costs (see Table 3). .

Biomass gasifier was modeled based on experimental data obtained at LabDER [29] laboratory at UPV, where it was designed and constructed prior being installed at ISTA. Gasification plant technology was a downdraft fixed bed, fabricated as a mobile unit to facilitate its operation and educational purposes at ISTA. Lifetime operating hours of the gasifier unit was 20,000 hours considering a minimum load ratio of 90%. Syngas generated in this system was converted to electric power by generation through an internal combustion engine with a conversion efficiency of 22%. Compared to published values in the open literature [30,31] resulted parameters of operation at maximum load conditions were very similar to the corresponding ones in similar systems, as detailed at table 2.

Parameters	ISTA Gasifier	Literature Range Min-Max
Gas generation per kg of biomass, Nm^3/kg	2.1	2-2.5
Electrical generation per kg of biomass, kW/kg	0.9	0.7-1.5
Input air per gas produced, Nm^3/Nm^3	0.7	0.5-0.8
Maximum gas LHV, kJ/Nm^3	6600	4000 - 7000
Efficiency of the conversion biomass-gas, %	79%	65%-85%
Efficiency of the conversion gas-electricity using a IC Engine, %	22%	18%-32%

Table 2. Gasification Plant Operation Parameters

3. Simulation

As mentioned in previous sections, simulation of the system was carried out with HOMER as it is widely used and accepted in literature [32,33,34]. System configuration of ISTA HRES was introduced as input data of the model, together with the unitary technology cost (solar and gasification) and the dispatch strategy.

Input Data	**Values**
PV Power Installed	10 kW
PV Cost	2.3k€/kW_{PV}
Replacement PV Cost	1.5 k€/kW_{PV}
O&M PV Cost	0.015 k€/kW_{PV}
Gasification Plant Power Installed	10 kW
Gasification Cost	7.7k€/kW_{GASF}
Replacement Gasification Cost	3.8 k€/kW_{GASF}
O&M Gasification Cost	1.0 €/hr

Battery Bank	10 kW
Battery cost	1200 € per unit
Battery Replacement Cost	1100 € per unit
Battery O&M Cost	50 €/yr
Converter	8 kW
Rectifier	8 kW
Dispatch Strategy	Load Following

Table 3. Input Data for HOMER simulation

Results of HOMER simulation of the ISTA system showed an annual AC energy consumption of 19,939 kWh, and a generation of 24,842 kWh. This energy production corresponds to a generation share of 76% Solar PV and 24% biomass gasification plant, equivalent to 18,875kWh/yr and 5,967kWh/yr, respectively. The excess of energy generated is due to the fact that two main constrains were imposed: a) the system had to be 100% renewable; and b) demand had to be 95% met. Figure 7 shows the monthly average power generated by the Solar PV and Biomass Gasifier per month.

Major gasifier generation was required during the months of Feb, Mar, Jun, Oct, Nov, while in Aug electricity load was practically covered by Solar PV

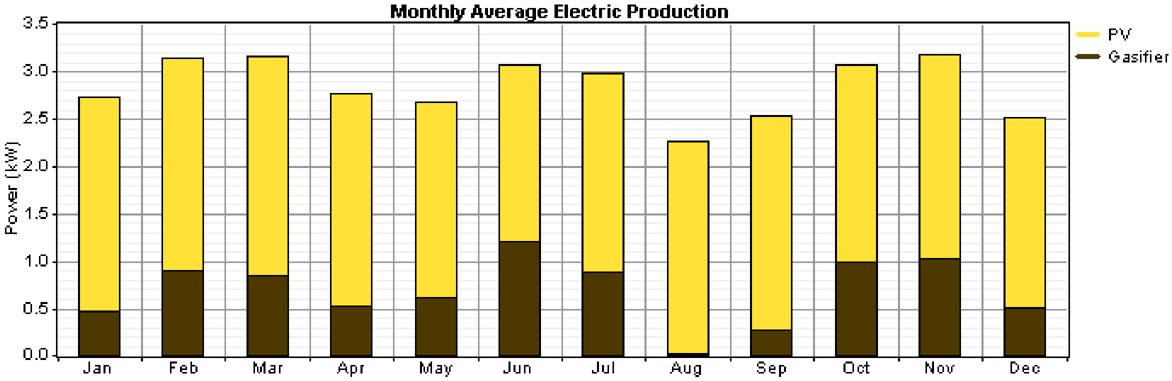

Figure 7. Monthly average power of ISTA HRES

It is evident that Solar PV dominated the electricity generation, while biomass gasifier was used as a backup generation unit. With the assumed system, the Solar PV power penetration with respect to the average load is 92.3%, which corresponds to the percentage of average power output of the PV array in relation to the average load.

Output Parameters	**Values**
P capacity	10 kW
Mean output	2.15 kW
Mean output	51.7 kWh/d
Capacity factor	21.5 %
Total PV production	18,875 kWh/yr
Minimum output	0.0 kW
Maximum output	9.58 kW
PV penetration	92.3 %
Hours of operation	4,380 hr/yr
Levelized cost	0.122 €/kWh

Table 4. Solar PV Plant output parameters

Output parameters of the gasification plant showed that it operates 663 hr/yr (capacity factor of 6.81%), produced 5,967 kWh/yr and consumed 6.28 tons of biomass annually. Operational strategy consisted on following the demand and recharging the batteries bank when it is lower than 30%.

Parameters	Values
Hours of operation	663 hr/yr
Number of starts	594 starts/yr
Operational life	30.2 yr
Capacity factor	6.81 %
Electrical production	5,967 kWh/yr
Mean electrical output	9 kW
Min. electrical output	9 kW
Max. electrical output	9 kW

Table 5. Gasification Plant output parameters

HOMER economic simulation provided the expected results. Initial capital cost of ISTA HRES was 119,400€ and operating cost 2,918 €/yr, with a total cost of 150,552€ and cost of energy in the order of 0.707 €/kWh. This cost considered the fact that it was necessary to produce excess of electricity in order to meet 95% of the demand. However, cost may be reduced by minimizing this excess of electricity by introducing demand side management strategies.

Analysis of the emissions showed that the micro power HRES installed at ISTA saved 5,242 $kgCO_2$ per year of operation in comparison with the traditional backup fossil fuel generator, while meeting the electrical needs of the building. This was a significant reduction of emissions in comparison with traditional methods of energy supply in DRC.

Based on previous analysis, it is concluded that the solar-biomass hybrid system was a viable option for its location at ISTA. Main generation was produced by solar PV, while gasification plant was an important complement for the solar PV in order to offer an energy supply environmentally friendly and assure the energy supply even in case of no PV availability, due to lack of solar radiation or PV system failures.

4. Experimental verification of the system stability

In the previous section, the renewable hybrid system installed at ISTA, consisting of a photovoltaic system and a biomass downdraft gasifier with stored electrical energy in a battery bank, was initially optimized and then, modeled. Next, its operation was simulated by HOMER to study the annual variation of solar radiation profiles together with the energy requirements of ISTA building, concluding that the system guaranteed its energy supply. Furthermore, this section shows the results of testing the technological feasibility of the system by carrying out several experiments in LabDER.

Experiments, reproducing the configuration of the ISTA RES with a scale factor of 1: 5, including photovoltaic solar panels, biomass gasifier and a battery bank with 2 kW each, were conducted to analyze whether ISTA renewable system was able to meet load needs at all times while maintaining an acceptable level of power supplied stability in voltage and frequency. Demand profile was reproduced using a programmed load, providing a temporal profile similar to the one registered at ISTA Center and used in the developed model described in previous section. Conclusions of the investigations demonstrated that it was possible to cover the electrical demand for ISTA Laboratory building. In numerous tests with different levels of solar radiation, RES was always able to cover the load demand.

Figure 8 plots the results of an experiment where, for a long period of time (in the order of several hours), the PV production was below the demand requirement. HRES generation responded to the predefined demand profile with the total energy supplied by various renewable sources (solar and biomass). From the difference between the two measured magnitudes: total generated power and power transmitted to the load, it was possible to deduce the losses in the transmission systems that are about 4% of the total power.

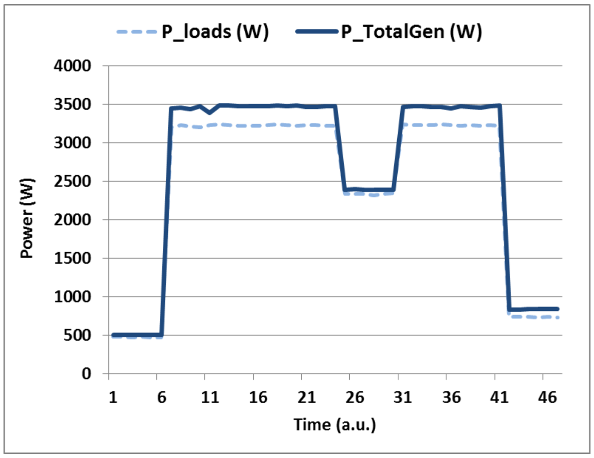

Figure 8: Power generated and transferred to the load

At the beginning of the experiment, in the absence of solar radiation and full charged storage bank, demand was met with the electricity stored in batteries (Figure 9). Once solar radiation period begins, Solar PV generation partially covered the electrical requirements while the rest was obtained from energy stored in the batteries until the bank decreased to a charging level of 30%. At this moment, biomass gasifier started, covering the demand and recharging the storage bank.

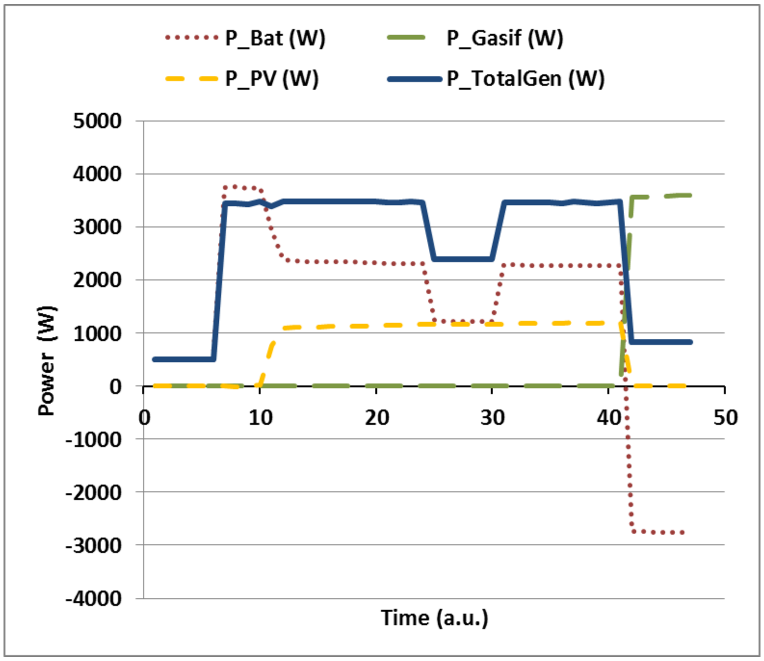

Figure 9: Contribution of each energy source

Gasification plant continued in operation until storage was again full charged, which allowed beginning each day with similar conditions (batteries at 100% of charge) and stablished a standard sequence of operation based on a working schedule. Figure 10 represented a whole cycle of operation for the biomass gasifier and the batteries charge level evolution with time.

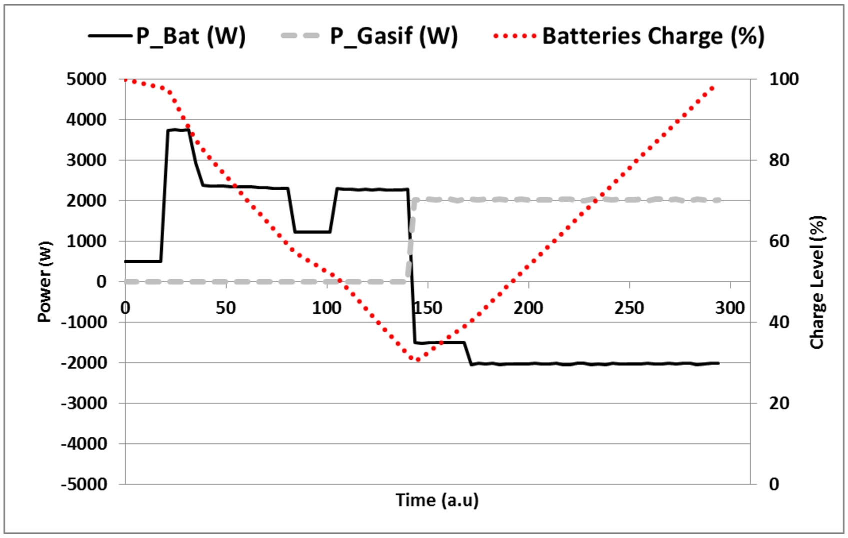

Figure 10: Batteries bank charge evolution

Finally, it was evaluated the HRES quality of the electric power generated by monitoring voltage and frequency of the output power in the load. Figure 11 showed the results. Minor fluctuations of 0.5% in voltage and 2% in frequency were obtained. It was denoted that frequency data varied at the end of the sequence when gasification plant started. This is because biomass gasifier fed a syngas engine with grid control which was less stable than the one defined by the batteries.

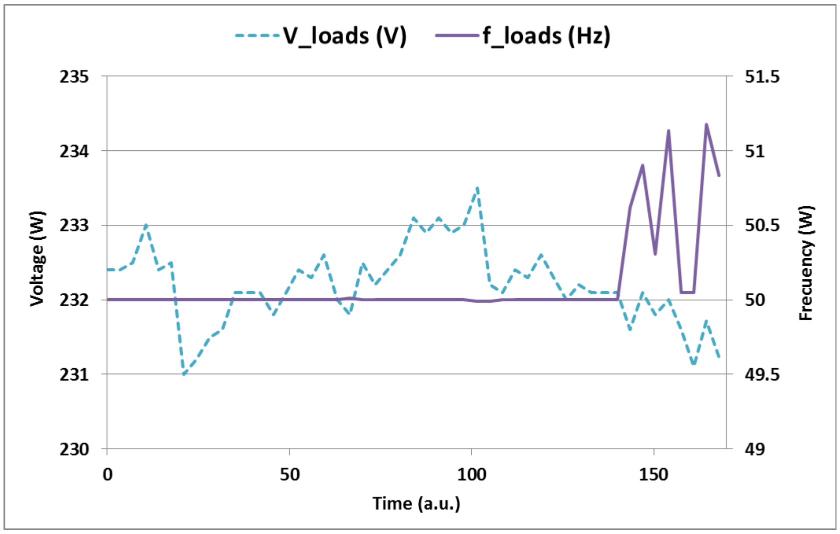

Figure 11: Voltage and frequency of the generated energy

In conclusion, the experiments performed in LabDER indicated that HRES designed for ISTA operated satisfactorily to meet the needs of the building and it may be operated with a high feasibility behavior and following a sequence of highly repetitive steps to facilitate its daily operation. Solar-Biomass RES was constructed according to the design parameters and it is currently in operation at ISTA with an operating procedure similar to LabDER experiments.

5. Conclusions

Hybrid Renewable systems including energy storage are especially suited for isolated area energy supply when high feasibility is required. A system composed by biomass gasification and photovoltaic solar panels with backup from electrical battery bank were designed and experimentally tested in its capability to fully supply a high feasibility application as is the case of the ISTA Laboratory building. Results indicate that stability in the electricity generated can reach a 98% and the demand can be fully covered if the renewable sources and the storage system are adequately dimensioned. The system has been built and it is now in operation at ISTA in DRC. Given the variation in demand and solar generation along the year, a surplus in generation of electricity was produced that cannot avoided if full demand coverage at any time is required and a fixed time operation for the gasifier is intended. Use of this energy surplus would require a second energy storage system that could be based on the storage of the extra syngas generated by the biomass gasifier.

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