Optimizing the size of a hybrid renewable energy system using various types of storage technologies

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Abstract. Hybrid renewable energy (HRE) systems without connection to the grid have a series of drawbacks due to the lack of reliability in the predictability of the climate, for this reason it is necessary to achieve the optimal sizing of the system components together with reliable storage systems to ensure the correct energy supply. At present commercially there are several storage technologies, lead acid batteries are the most used however they are losing space compared to lithium ion in stationary applications despite the uncertainties for cost and profitability, another technology is pumped hydro, appears as a clean solution unlike the previous ones. In this document the hybrid system composed of photovoltaic panels, a biogas generator and the three types of storage individually by means of technological tools is optimized, the result of the techno-economical simulation indicates that the system with pumped hydro has the lowest energy cost (COE) with 0.299 $/kWh, while the system with acid lead batteries has the highest energy cost at 0.401 $/kWh but has the lowest initial project cost 1.05 M$, lithium ion batteries reach a longer life time.

1. Introduction
The Paris agreement signed on December 12, 2015 by 197 countries, seeks to substantially reduce greenhouse gas emissions and limit the increase in temperature to 2 °C in the coming years [1], during the discussion of the agreement consensus was reached between scientists and politicians on the depletion of non-renewable resources and to continue with the rate of environmental pollution will reach catastrophic consequences in the coming decades. One of the main pollution sectors is energy, therefore short-term actions must be taken to mitigate the impact of energy consumption even more when evidence reveals that current consumption rates are not sustainable in the long term [2]. On the other hand, in isolated communities the use of generators based on fossil fuels is becoming more common, which is not viable due to environmental issues, in addition to the volatile costs of fuels and the difficulty in transport leads to be unattractive. The renewable energies are a solution to the energy problem and to reduce environmental pollution, in recent years with the advancement of technology in renewable generation systems has been promoted the increase in the implementation of solar plants, wind farms and biomass-based generators with marginal energy costs, but for small isolated hybrid systems the cost is not yet competitive due to the price of the storage components [3]. The storage system has two functions, one is to store energy of the renewable generators when the consumer does not need and the second is to deliver the stored energy when the generators cannot meet the total demand in the charge, additional has features such as smoothing the instabilities of the network due to the intermittency of several meteorological variables and improve the quality of the energy that is directly linked to the sizing of the storage bank.
One of the first challenges in the implementation of generation systems is the technical dimensioning due to the intermittency of renewable sources so it becomes a hard task, because the low predictability and sudden changes of the weather, in the literature of high impact has been proposed methodologies to follow, optimization algorithms together with specialized software’s to achieve the optimal sizing [4, 5].

In the reference [6] the authors indicate that in a micro-grid is the right sizing of the battery bank therefore the system will have a better performance and efficiency unlike non-optimized renewable energy systems, the authors propose a new methodology to found the optimal size where storage technology, life time and degradation of the equipment are involved, the proposed model uses linear programming of mixed integers (MILP), the results are verified by a numerical simulation with historical meteorological and load data.

Mulleriyawage [7] in his research describes that residential battery banks are in except because of the high market price, the optimal size can reduce costs so it can be economically reasonable, the aim of the work is to minimize the price of energy, including the total price of installation based on the maximization of self-consumption, the case study was carried out in Australia, the results show that the implementation is profitable with current market prices as long as the current government incentives are maintained according to the capacity of the SF, a tariff scheme for time of use is more convenient than a self-consumption system, with a better return on investment, lower net current cost and reducing the emission of polluting gases.

Fareeha [8] presents his research work where he aims at the economic technical design of a HRE system for remote areas, the optimization problem has been solved by means of the HOMER software depending on the management of demand and the type of storage, in the document the performance of four cases is evaluated for the solution of the problem posed, the resulting system will result in the lowest overall cost of the system increasing the efficiency and performance of the same.

Various software’s are used around the world which are a powerful tool for the sizing, analysis, feasibility study of hybrid systems [9–11].

According to the above, the main objective of the work is the optimal sizing of the hybrid system with different types of storage taking advantage of the resources of the locality, the comparative analysis of the different scenarios based on the price of energy, initial cost, reliability and energy balance. The article is structured as follows: the second section presents the description of renewable sources and the model of the hybrid system. The third section describes the system optimization for each of the selected technologies. The fourth section discusses the results obtained. The final part includes the conclusions of the work.

2. Description of the system

The hybrid system without connection to the grid will meet the energy needs of the loads and offices of the solid waste dump of the Iguanas in the city of Guayaquil, being the main place of collection of urban solid waste in the country.

The characteristic curve is of commercial type, this is presented in Figure 1, the estimated power is 438.9 kW, during the night the load is low, in the day it is where there is the greatest demand.

The work aims to optimize the components of the hybrid system of renewable energies using different storage technologies to know the competitive and economic advantages of the systems, to achieve the objective three types of technologies are used, in the first analysis acid lead batteries are used which are the most used, the second analysis is by lithium ion batteries, batteries widely used in portable devices and the third analysis is by means of hydraulic pumping, which is a technology that makes its way in the market has the advantage of not emitting polluting’s.
2.1. Solar radiation
The solid waste dump of the Iguanas is located at coordinates -2.083, -79.954, solar irradiance values are from NASA, the site under study has an important solar resource with an average of 4.58 kW/m2/day. The monthly irradiance data are shown in Figure 2.

![Energy demand](image)

**Figure 1.** Characteristic demand curve.

![Solar Resource](image)

**Figure 2.** Monthly solar resource values

2.2. Modelling of the photovoltaic system
Photovoltaic solar panels convert solar energy into electricity through the photoelectric effect. The output energy of the photovoltaic field can be calculated using equation 1 [5]:

$$E_{PV} = E_{RPV} \times PR_{PV} \times \left( \frac{G_T}{G_{T,STC}} \right) \times \left[ 1 + \beta_P \times (T_C - T_{C,STC}) \right]$$

(1)

Where; $E_{RPV}$ is the nominal power of the photovoltaic generator (kW), $PR_{PV}$ is the reduction factor (%), $G_T$ is the solar irradiance over the receiving plane (kW/m2), $G_{T,STC}$ is the solar irradiance under standard test conditions (STC), $\beta_P$ is the temp coefficient (%), $T_C$ is the temp of the photovoltaic cell, $T_{C,STC}$ is the temp under STC.

2.3. Biomass
Municipal solid waste (MSW) is garbage or waste generated by urban areas, waste is composed of organic waste from food, paper, wood and inorganic waste such as glass, plastic and metals, depending on the recycling processes implemented by local governments, certain household waste arrives at the landfill, these wastes are not classified as hazardous. There are two types of landfills according to the collection of waste, the organized landfill horizontal pipes are installed for the collection of biogas, while the vertical pipes are placed at the time of accumulating the landfill, the gas can be extracted between 8 and 12 years. While in the unorganized landfill the filling is placed without horizontal or vertical pipes, which have to be placed when the capacity of the landfill is completed, the top is filled with concrete, the biogas extraction time is 3 to 7 years. Fuel gas can be used in internal combustion engines [12], [13]. Agreements between caf and the municipality of Guayaquil will allow the use of methane gas from the Iguanas dump, the project consists of the design of incorporation of 65 wells for the extraction of gas reducing 260,000 tons of carbon dioxide equivalent per year [14], the city of Guayaquil has a production of 3419 tons / day of solid waste [15].

2.4 Modeling of gasifying biomass
Biogas is produced by bacteria until it finish the process of biodegradation of matter in the absence of air or anaerobic, this process is natural in landfills controlled by urban solid waste, methane is the main component of the gas, the energy value total of biomass is dependent by the concentration of gas methane. The power generated is obtained by equation 2.

\[
P_{MTG} = \frac{Q_{BM} \times \eta_{BMG} \times CV_{BM} \times 1000}{DOH_{BMG} \times 365 \times 860}
\]

Where, \(Q_{BM}\) is the amount of annual biomass measured in tons, \(\eta_{BMG}\) is the throughput of the biomass generator, the calorific value of the matter is \(CV_{BM}\), \(DOH_{BMG}\) is the daily hours of operation of the generator and 860 is the conversion value from kcal to kWh.

2.5 Types of storage technologies
The correct energy storage allows the flexibility and reliability of the system, several technologies have been developed to drive the transition to decarbonized electrification. Each one offers certain advantages regarding the design and type of function to be performed.

2.5.1 Lead acid batteries. This type of batteries have been widely used for HRE systems both in the energy backup and the stability of the grid, these elements are composed of two electrodes immersed in an electrolyte so that chemical reactions occur, currently according to the technology used they can be divided into several categories. Lead-acid batteries are the oldest rechargeable and widely used due to the low cost and a considered number of operating cycles but among the disadvantages is the low energy density, a low lifetime compared to another type of battery and the explosive gases it emits. The loading process can be calculated using equation 3.

\[
E_{Bat}(t) = (1 - \alpha) \times E_{Bat}(t - 1) + \left( E_{L}(t) - \frac{E_{L}(t)}{\eta_{Conv}} \right) \times \eta_{CC} \times \eta_{rBat}
\]

2.5.2 Hydraulic Pumping. It is one of the clean storage technologies, and the principle of operation of hydraulic pumping is to drive water from a lower tank to a higher one when you have an excess of energy, when the load requires energy the water of the upper tank falls moving a microturbine producing.
electrical energy. It is a mature technology which does not involve environmental pollution [16], to calculate the energy needed to pump the fluid from the lower tank equation[16] (4) is used, the volume of fluid is V, h is the distance from the upper tank, \( \eta_p \) is the throughput of the pumping system while the energy generated by the microturbine can be calculated using equation (5), where \( \eta_g \) is the generation throughput.

\[
E_{\text{pumping}} = \frac{\rho \cdot g \cdot h \cdot V}{\eta_p}
\]  

(4)

\[
E_{\text{generator}} = \rho \cdot g \cdot h \cdot V \cdot \eta_g
\]  

(5)

2.5.3 Lithium batteries. Lithium batteries is the result of technological development (LiFePO4), batteries have some advantages over their competitors such as not suffering from the memory effect and being able to charge at any time of the state of charge, they have a higher density of capacity and storage which has as a consequence a longer life time reaching up to 15 years. The maintenance is almost zero without emitting polluting gases by not presenting self-discharge.

The energy total storage by the battery bank can be calculated using equation 6. Where \( B_{\text{bat},0} \) is the initial charge of the battery bank, \( V_{\text{bat}} \) is the battery voltage, \( I_{\text{bat}} \) is the battery current.

\[
B_{\text{bat}} = B_{\text{bat},0} + \int V_{\text{bat}} \cdot I_{\text{bat}} \, dt
\]  

(6)

3. Simulation and results

The different configurations according to the selected technologies are simulated in HOMER to achieve optimal sizing, the result of each of the systems is evaluated by three parameters 1) price of energy for kWh, 2) the cost of capital starts l which are the economic resources that are needed to start the project, 3) NPC, is the present value of all component costs over the life of the project.

3.1 System proposal

The selected solar panels are from the Jinko eagle per 60/300w with an efficiency of 18.33%. The biogas generator is from the manufacturer Jenbacher JGC 420 B81 with an electrical power of 1,416 kW. The inverter is from the manufacturer Fronius Symo with a power of 20 kW per unit.

3.1.1 PV, Biogas, Lead Acid Battery system. The scheme of the first proposed system to be studied is shown in Figure 3, the resulting optimal system is conformed by a photovoltaic matrix of 123 kW, 1 generator Jenbacher J420,493 batteries of the manufacturer Trojan SSIG 12 120 has a capacity of 118 Ah and 3 converter of 20 kW mark Fronius.
The photovoltaic array has an average output of 19.6 kW, with a maximum output of 116 kW, the total production is 172,021 kWh/yr, the cost of energy is 0.0959 $/kWh, the biogas generator has an electricity production of 1,738,294 kWh/yr starting 386 times a year, the operational life time is 8.20 yr, the efficiency of the equipment is 13.9%, the operating cost is 18.6$/hr and the marginal operating cost is 0.0759 $/kWh. The battery bank is composed of 493 units with a nominal capacity 698 kWh, the storage system has a range of 5.53 h, the life expectancy is low with 1.78 years, delivering 193,256 kWh over the operating time, the energy stored in the battery is 121,192 kWh/yr, the losses in the battery are 24,278 kWh/yr.

The optimization achieves the following economic results, the total cost of installation is 4.58M USD (NPC), initial capital is 1.05M USD, the annual operating cost is 273,188 $/yr and the levelized price of energy (COE) is 0.401 USD/kWh.

During the entire time of operation of the project, the element that has a higher cost is the biogas generator of 3,211,192.24 $ followed by the group of batteries with a total cost of 1,136,952.30 $ and also with the cost per operation and maintenance with 127,465.31 $.

3.1.2 PV, Biogas, Lithium system. The system is made up of a photovoltaic generator of 120 kW, 1 biogas generator Jenbacher J420, 375 lithium batteries with a capacity of 100 Ah, 5 inverter of 20 kW Fronius, in figure 4 the configuration of the system is shown. The total energy production of the system is 1,873,911 kWh/yr, has an excess energy of 982,900 kWh/yr, the unsatisfied load is 0% which guarantees the energy supply.

The photovoltaic generator has an average output of 19.1 kW during the day, the maximum output of the generator is 113 kW, the total production is 167,426 kWh/yr, the energy cost of 0.0959 $/kWh with a yield of 15.9%, the biogas generator has an electricity production of 1,706,566 kWh/yr with an average output power of 356 kW, the equipment starts 407 times a year, the life time of the generator is 8.36 yr, the efficiency of the equipment is 13.7% and the marginal cost of operation is 0.0759 $/kWh. The lithium battery bank is composed of 375 units with a nominal capacity of 480 kWh, the battery bank has a range of 4.75 h, the life expectancy is high with 16 years, delivering 1,680,000 kWh during the operation of the project, the energy stored in the battery is 106,970 kWh/yr, the losses in the bank are minimal compared to another type of storage with 4.284 kWh/yr.

The total price of the components where it includes the initial capital, change of equipment and maintenance is 3,925,872.12 dollars, the initial capital is 1.29M operating cost is 203,513 dollars and the price of energy is 0.343 $/kWh. The equipment that has the highest cost is the J420 generator with 3,157,197.94 followed by the battery bank with 531,485.86, the equipment that has a higher cost per maintenance operation is the biogas generator with 61,884.02 dollars.
3.1.3 PV, Biogas, Pumped hydro system. The third system consists of a photovoltaic generator of 135 kW, 1 biogas generator Jenbacher J420, 5 pumped hydro 245 kWh, 5 inverter of 20 kW Fronius, the scheme is presented in Figure 5. The total production of the system is 1,741,495 kWh /yr of which 1,552,914 kWh corresponds to the biogas generator, the excess energy is 824,753 satisfying the load at 100%.

| Systems                     | COE ($) | NP C ($) | Operating cost ($) | Initial capital ($) | Renewable Production (kWh) | Losses Storage (kWh) | Autonomy Storage (h) | Annual Throughput Storage (kWh) | Expected life Storage (yr) |
|-----------------------------|---------|----------|--------------------|---------------------|---------------------------|----------------------|----------------------|-----------------------------|--------------------------|
| PV/Biogas/B Lead Acid       | 0.40    | 4.58     | M 273,188          | 1.05 M              | 1,910,315                 | 24,278               | 5.53                 | 108,722                     | 1.78                     |
| PV/Biogas/B Lithium         | 0.34    | 3.93     | M 203,513          | 1.29 M              | 1,706,566                 | 4,284                | 4.75                 | 105,060                     | 16                      |
| PV/Biogas/Pumped Hydro      | 0.29    | 3.42     | M 182,863          | 1.06 M              | 1,741,495                 | 29,511               | 12.6                 | 11,309                      | 7                       |

The photovoltaic system has an average of 21.5 kW the total production is 188,581 kWh/yr, the energy cost of 0.0959 $/kWh with a yield of 15.9% running for 4,404 hrs/yr, the biogas generator has an electricity production of 1,552,914 kWh/yr starting for 443 times a year with a yield of 12.4%, the average output power of the J420 is 356 kW, the operating life time is 9.18 yr, while the marginal cost of operation is 0.0759 $/kWh.
The storage system is composed of 5 hydraulic pumping units of 245 kWh, the system has 12.6 hr of autonomy, the nominal storage capacity is 1,271 kWh, the energy delivered is 979,982 kWh for the 7 years of operation, the energy lost in the system is 29,511 kWh/yr.

The optimization achieves the following economic results, the total cost of installation is 3.42M USD (NPC), the initial capital is 1.06M USD, the annual operating cost is 182,863 $/yr and the level cost of energy (COE) is 0.299 USD/kWh.

The total cost of the project is 3,424,427 dollars, the element that has a higher cost is the biogas generator of 242,569.93 $ followed by hydraulic pumping but with a large difference of about 90% with a total cost of 1,136,952.30 $ but the highest cost is in the area of operation and maintenance with 129,275.17 dollars.

4. Economic result of the systems

In the Table 1 presents the result of the different systems analysed, the scheme formed by hydraulic pumping achieves the best results with the lowest cost of energy and a considerable life of the system, the state of charge (SOC) indicates the energy stored in the storage system, the indicator is presented in percentage, in the Figure 6 the SOC of the pumped hydro is shown, when it is at 100% the upper reservoir is completely full, when it reaches 0% the upper reservoir is empty therefore it has no energy backing in case of needing the load.

![Figure 6. Generic 245 kWh Pumped Hydro State of Charge](image)

In few occasions the load consumes 100% of the energy stored in the reservoir, while in the year the stored energy is at 100%, figure 6 shows in positive the power input that enters the reservoir of the system and in negative the power that is delivered by the reservoir.
4.1 Comparison of greenhouse gas emissions
The first system made up of lead acid batteries emits 850,969 kg / yr of carbon dioxide, 2,830 kg / yr of carbon monoxide, 79.8 kg / yr of particulate matter and 5,937 kg / yr of nitrogen oxides into the environment. The second system made up lithium of lithium batteries emits 835,437 kg / yr of carbon dioxide, 2,778 kg / yr of carbon monoxide, 78.3 kg / yr of particulate matter and 5,829 kg / yr of nitrogen oxides. The third system made up of pumped hydro emits 760,218 kg / yr of carbon dioxide, 2,528 kg / yr of carbon monoxide, 71.3 kg / yr of particulate matter and 5,304 / yr of nitrogen oxides. The last system analysed has the best indicators regarding the gases emitted into the environment.

5. Conclusions
In the article the optimization of the hybrid system taking advantage of the generation of biogas from municipal solid waste is analyse, the behaviour of three types of storage technology is compared and evaluated, the first analysis was carried out with lead acid batteries having the highest cost of energy with 0.401 $ / kWh, a lower expectation in the life time with 1.78 years, however it presents the lowest initial cost of the system so it remains one of the preferred ones, it also has very high energy losses with 24278  kwh/yr ,the second technology analysed to are lithium batteries, the leveled cost of energy is 0.343 $/kWh , has the highest initial cost of the three systems studied with 1.29 M USD, but also has the highest life expectancy with 16 years.
The best result has the hydraulic pumping system with a photovoltaic generator of 135 kW, a biogas generator J420, 5 hydraulic pumping systems, the cost of energy is 0.299 $/kWh.
The size of the photovoltaic generator varies according to the type of storage system, with lithium batteries the smallest PV size is achieved.

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