Evaluation of the energy potential of urban waste wood by gasification

Evaluación del potencial energético de la madera residual urbana mediante gasificación

Lili Vega[2]
Andrés Herrera[3]

[1] Inter-administrative Agreement 001 - 899 signed between the UAESP and the JBB, start date July 1, 2015, end date December 31, 2016.

[2] Colombian Candidate to MSc. Mechanical Engineering. Contractor. Botanical Garden of Bogotá José Celestino Mutis, Colombia. E-mail: ltvegac@unal.edu.co

[3] Colombian. Candidate to MSc. Watersheds. Contractor. Special Administrative Unit of Public Services UAESP, Bogotá, Colombia.E-mail: anheag@gmail.com

Received: 24- 07 - 2017 Accepted: 03-05-2018

How to cite: Vega, L., & Herrera, A. (2018). Evaluation of the energy potential of urban waste wood through gasification. *Informador Técnico,* 82(1), 26-41. doi: http://doi.org/10.23850/22565035.888

Abstract

The energy potential of the urban residual wood (MRU) of the Capital District was evaluated, from furniture, carts, crates, and pallets, through the gasification process in the generation of electrical energy using the Power Pallet ® system of the Botanical Garden of Bogotá. The MRU was classified into two categories from a board of medium density fiber or wood chipboard (MDF) and without agglomerate, analyzing the physicochemical characteristics of the two types of biomass, the performance of the system, the operational variables such as temperature, power, biomass consumed, energy performance, and an economic analysis of the production of electrical energy through the use of this type of waste. According to the technical evaluation, it is concluded that the Power Pallet ® technology is not the most suitable for the use of the MRU, due to the restrictions of the particle size and the cleaning of the synthesis gas. According to the estimated annual average amount of urban residual wood of 144,667 tons, the maximum power that the District could install would be around 20 kW electric. Although this potential is low compared to other types of biomass, it is an alternative that will allow the valorization and reuse of the MRU.

Keywords: urban solid waste; renewable energy; energy security, wood agglomerate; waste energy assessment.

Resumen

Se evaluó el potencial energético de la madera residual urbana (MRU) del Distrito Capital, proveniente de mobiliario, carretas, guacales y estibas, mediante el proceso de gasificación en la generación de energía eléctrica empleando el sistema Power Pallet ® del Jardín Botánico de Bogotá. La MRU se clasificó en dos categorías provenientes de un tablero de fibra de densidad media o aglomerado de madera (MDF- por sus siglas en inglés) y sin aglomerado, analizando las características fisicoquímicas de los dos tipos de biomasa, el desempeño del sistema, las variables operacionales como temperatura, potencia, biomasa consumida, desempeño energético, y se realizó un análisis económico de la producción de energía eléctrica mediante el aprovechamiento de este tipo de residuo. De acuerdo con la evaluación técnica, se concluye que la tecnología Power Pallet ® no es la más adecuada para el aprovechamiento de la MRU, debido a las restricciones del tamaño de partícula y a la limpieza del gas de síntesis. De acuerdo con la cantidad estimada promedio anual de madera residual urbana de 144.667 toneladas, la potencia máxima que podría instalar el Distrito sería alrededor de los 20 kW eléctricos. Aunque este potencial es bajo comparado con otros tipos de biomasa, es una alternativa que permitirá la valorización y reutilización de la MRU.

Palabras clave: residuos sólidos urbanos; energías renovables; seguridad energética, aglomerado de madera; valoración energética de residuos.

Introduction

All material in a solid, liquid or gaseous state, either isolated or mixed with others, resulting from a process of extraction of Nature, transformation, manufacture or human consumption, which its owner decides to abandon is considered waste (Jaramillo and Zapata, 2008). Those residues that are generated in urbanized spaces, as a consequence of consumer activities and management of domestic activities (housing), services (hospitality, hospitals, offices, markets, among others.) And some industries are classified as Urban Solid Waste (RSU) (Jaramillo and Zapata, 2008). The RSU contains a significant fraction of paper, food waste, wood and pruning cuts, cotton and leather, metals and glass, as well as petroleum derivatives such as plastics, rubber and synthetic fabrics (Moratorio, Rocco, and Castelli, 2012).

In Colombia, around 25,000 tons of solid waste are produced per day, of which 13 % recover and reintegrate in the productive cycle, and 7 % are recovered and commercialized (Fernández, Martínez, and López, 2015). At the national level, the final disposal is carried out in authorized sites such as contingency cells, utilization plants, and sanitary landfills; and sites not authorized by environmental authorities, such as temporary cells, burning, dumps and water bodies (Superintendencia de Servicios Públicos Domiciliarios, 2015).

According to the Ministry of Environment and Sustainable Development, the Capital District produces approximately 6,429 tons of solid waste daily, which translates into 2,346,826 tons per year, of which 60 % are of usable character, that is, with potential for recycling, reuse and other types of utility (Fernández *et al.*, 2015). Of this waste, 27 % corresponds to food, followed by plastic and paper waste with 19.15 %, and 0.49 % corresponds to wood (UAESP, 2011).

Under the framework of the Comprehensive Solid Waste Management Plan (PGIRS), multiple alternatives are proposed for the management of the RSU, from separation at source (organic, recycling and unusable), transformation (composting, waste energy recovery) and the final disposition. The Exploitation Program, developed in the PGIRS, proposes the quantification and characterization of waste to determine the potential for use (Minister of Housing, City and Territory, 2015). Following this guideline, in the case of waste wood, it is reported in the current market alternatives such as agglomerated board manufacturing, by separating, transporting and cleaning wood at efficient production costs (Primadera SAS, 2017), pellet manufacturing for combustion in stoves, boilers, among others. (Aruna, Laarman, Araman, Coulter, and Cubbage, 1997), wooden floors, carpentry elements for restoration projects (Bratkovich, Bowyer, Lindburg, and Fernholz, 2009), among others.

The Botanical Garden of Bogotá (JBB) and the Special Administrative Unit of Public Services (UAESP) under the inter-administrative agreement 889-JBB-001-UAESP signed in 2015, joined efforts in order to establish the technical feasibility of the gasification of Urban waste wood (MRU) for the production of electrical energy, as an option for the transformation of this type of waste. Although this option is not the definitive solution, its efforts are articulated for the recovery of the RSU, providing additional benefits such as the reduction of environmental impacts of the production of new products, the reuse, the creation of employment, and, in many cases, the reduction of existing costs, avoiding purchase/disposal costs. Enhancing the possibility of closing the life cycles of the RSU and generating added value, which is reflected in the production of electrical energy.

Gasification is a thermochemical process in which a set of chemical reactions occur in an oxygen-poor environment, resulting in the transformation of a solid into a series of gases that can be used in combustion. In this process, cellulose is transformed into lighter hydrocarbons, carbon monoxide, and hydrogen. The performance of the gasification process varies depending on the technology, the fuel and the gasifying agent used, in the range of 70-80 %. Through gasification, electrical outputs of up to 30-32 % can be achieved through the use of moto-generators powered by syngas (IDAE Institute for Diversification and Energy Saving, 2007). The process takes place in 3 stages: one of heating up to 100 °C, which allows the drying of the biomass by evaporation of the water contained in it. A stage called pyrolysis, in which the large molecules are broken, giving rise to other shorter chain molecules, which at the reactor temperature, are in the gas phase.

And, finally, an oxidation stage of the heaviest (carbonaceous) fraction of the biomass when in contact with the gasifying agent (air, oxygen, or water vapor) (IDAE, 2007, Pujoldevall Sánchez de Toledo, 2015). According to the contact method they use between the solid (biomass) and gaseous (oxidizing agent) phases, the gasifiers are classified as a fixed bed, fluidized bed and drag gasifiers. According to the bioenergy line, a size between 1 - 1.5 MW is practical for downstream gasifiers and when it comes to updraft there are plants with a size of 4-6 MWt (Held, 2012).

Materials and methods

The evaluation of the energy potential was carried out through the preparation, physicochemical characterization and the generation of electrical energy through the gasification of the MRU. The gasification and electric power generation process was carried out in the Power Pallet ® PP20 system, located in the Botanical Garden of Bogotá, José Celestino Mutis. The materials, equipment and methods used are detailed below.

Power Pallet ® PP20 system

The system consists of a GEK TOTTI series reactor, an automation system and a motor coupled to a generator (Figure 1).

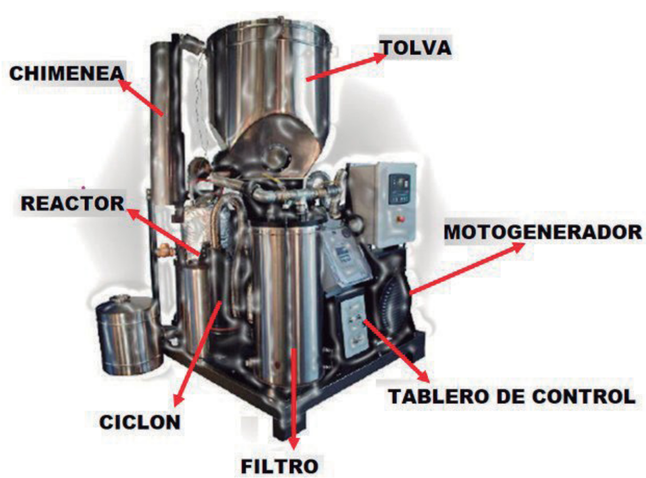

Figure 1. Components of the Power Pallet ® PP20 System
Source: adapted from (All Power Labs, 2014).

The system can be divided into two components: the thermochemical transformation, with air as a gasifying agent and the generation of electrical energy by a gas engine. With a continuous nominal power of 15 kW at 50 Hz and 18 kW at 60 Hz, a nominal consumption of 1.2 kg/kWh. According to the operation manual, the biomass used must meet the following requirements:

Particle size ½″ y ⅜″.

• Fixed carbon content around 20% or more in weight.

• Ash content less than 5%.

• Moisture content between 10-30 %, measured on a dry mass basis.

• Restriction temperature (in the home) between 800° -1000 °C.

• Reduction temperature (in the upper part of the basket) between 700° -800 °C.

Preparation and granulometric classification of urban residual wood - MRU

The wood from the pruning waste used in the Botanical Garden comes from an undetermined mixture of species present in the city of Bogotá, among which have been identified: Pine (*Pinus*), Eucalyptus (*Eucalyptus*), Cherry (*Prunus serotype*), Urapa (*Cytharexylon sub flavescent*), Guayacan (*Lafoensia acuminate*), Willow (*Salix* ps.), Acacia Morada (*Acacia baileyana*), Rubber (*Ficus stenosis*), Cedar (*Cedrela Montana*) (OpEPA, 2016, García, 1968).

The MRU from urban furniture, carts, pallets, and crates was provided by the UAESP. We used both natural woods obtained directly from tree trunks and artificial woods obtained from natural wood remains (barks, shavings, branches, etc.) as agglomerate boards, plywood boards, and fiberboards. For the gasification tests, the following classification of the MRU was performed (Figure 2).

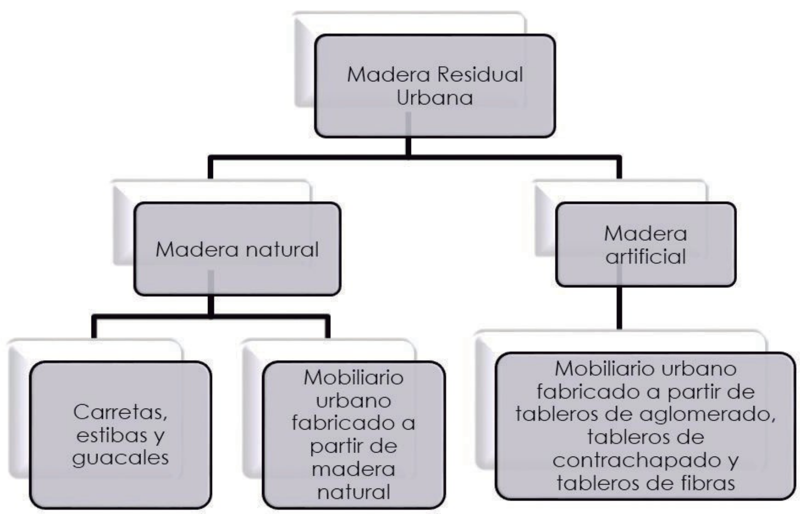

Figure 2. Classification of the MRU for physical-chemical tests
Source: the authors.

The preparation of garden pruning waste was carried out in accordance with the operation protocol, as shown in Figure 3. The preparation of the MRU began with the removal of all the tips, screws and plastics, to perform the reduction and the granulometric classification according to the specifications of the system.

Physical-chemical characterization

Figure 3. Conditioning of biomass for the gasification process
Source: the authors.

The following tests were carried out in accordance with international standards:

- The standard method for moisture content analysis: ASTM E871 standard.
- Standard test method for the determination of ash content: ASTM D 3174.
- Method for measuring the pH of wood chips, based on the standard T-435 om-02.
- Elemental analysis: ASTM D5373, ASTM D4239.
- Next analysis: ASTM E872-72, ASTM E870-82, ASTM D2016-74, ASTM D102-84.
- Calorific Power: ASTM D240.
- Thermogravimetric analysis TGA, ASTM E1131.
- Gas chromatography or gas composition analysis: ASTM E1131.

The physicochemical characterization as the next and last analysis was carried out for the 4 MRU samples and for the JBB residues. In the case of the composition of the synthesis gas and its calorific value, they were made for the gasification of MRU with and without MDF, and the JBB waste.

Power generation tests

Once the two samples of MRU were prepared, the electric power generation tests were carried out by means of gasification in the Power Pallet ® PP20 system, in accordance with the Protocol of Operation (All Power Labs, 2014). Three tests were carried out with their respective replica, making the registration of the following variables as shown in Table 1.

Table 1. Operationalization of variables

Independent Variables (Factors)	Indicators / characteristic dimensions	Techniques and measuring instruments
Type of biomass	Origin MRU with and without MDF, Waste pruning	Visual observation
Moisture content	% en peso	ASTM E871 Standard
Percentage of use	% en peso	kg suitable biomass / kg total biomass
Amount of biomass consumed	kg de MRU	Digital balance
Gives		
Dependent variables (Answers)	800°–1000 °C	Power Pallet® system, thermocouple type k
Restriction temperature	700°–800 °C	Power Pallet® system, thermocouple type k
(Trst)	0-18 kW	Power Pallet® System
Reduction temperature	kWh	Electricity meter

Source: the authors.

Evaluation of the energy potential of the MRU

The evaluation of the energy potential of the MRU was made by comparing the baseline of the system using pruning waste, which was made based on the percentage of use of biomass due to the granulometric classification, the consumption of biomass by an hour of operation, the heating ramp, the power generated. Additionally, the energy potential of the MRU of the city of Bogotá was determined.

Results and Discussion

Percentage of use

In accordance with the reduction and granulometric classification, the utilization percentage of the MRU was determined, which is shown in Table 2. It is observed that 39.1 kg (60 %) and 46.4 kg (47 %) of the biomass remains in the first granulometric classification (>1/2"), for the MRU-natural and MRU-artificial respectively, values well above that presented for the waste of pruning with 20 %. The above is represented in a low percentage of use for MRU samples, with 24 % and 25 %.

Table 2. Determination of the utilization percentage of the MRU and the baseline (Pruning residues)

Granulometric classification / Type of biomass	Pruning waste: Baseline	MRU-natural	MRU-artificial
Initial weight of biomass (kg)	42,5	39,1	46,4
Amount of biomass> 1/2 "(kg)	8,6	23,3	22
Amount of biomass <1/2 "(kg)	34,2	15,8	24,4
Amount of biomass> 3/8 "(kg)	20,4	9,6	11,8
Amount of biomass <3/8 "(kg)	13,8	6,3	12,6
% Exploitation	48%	24%	25%

Source: the authors.

Physical-chemical characterization

When determining the composition of the MRU (see Table 3) and the JBB mixture, they were found to be rich in oxygen and carbon. Important, highlight that the sulfur content is zero for all biomasses, which allows us to affirm that there will be no formation of sulfur oxides (SOx) causing corrosion, acid rain, and sulfates transported in respirable particulate material (IDAE and ESCAN, 2008). The MRU presents a high proportion of oxygen of 49 % and 45 % in carbon, which can be the cause of the reduction of the Lower Calorific Power - PCI, due to the low chemical energy contained in carbon-oxygen and carbon-hydrogen bonds. The presence of nitrogen in the sample of MRU with MDF, although low, may contribute to the formation of Nitrogen Oxides (NOx) that favor the formation of acid rain.

Table 3. Elemental analysis

Sample	Nitrogen	Carbon	Hydrogen	Sulfur	Oxygen*
Furniture	0,00	47,1539	5,7270	0,00	47,1191
Wagons	0,00	45,4835	5,5772	0,00	48,9393
Pallets	0,00	45,1833	5,6876	0,00	49,1292
JBB	0,00	43,6711	5,0551	0,00	51,2738
MRU- with MDF	1,2324	43,7743	5,3036	0,00	49,6897

*The values are calculated
Source: the author.

In Table 4, the result of the next analysis can be observed. The moisture content of less than 10 % is in accordance with the requirements established by the manufacturer of the gasification equipment. This low moisture content will be reflected in a shorter drying stage. The ash content affects the energy available from the biomass and in turn affects the costs of processing and transforming the energy of the same (IDAE and ESCAN, 2008). A percentage of less than 5 % is favorable, because of the above and there will be no slag formation (Bratkovich *et al*., 2009). Regarding the percentage of volatile matter (80 %) and fixed carbon (19 %), this will be beneficial for gasification if high values are present since it is reflected in a high caloric energy contained in synthesis gas, representing the ease with which biomass can be burned, gasified or oxidized (IDAE, 2007). The content of volatile matter was higher than the recommended 10 %, therefore, for this type of biomass, it is more advisable to use it in mobile bed gasifiers in parallel current (Rocha, Vesga, and Pinto, 2011, Fonseca González, 2003).

Table 4. Close analysis of biomasses

Sample	Humidity % (m/m)	Volatile matter % (dry basis)	Fixed carbon% (m/m) (dry basis)	Ash % (m/m) (dry basis)	pH
Mobiliario	7,623	79,924	19,746	0,330	4,48
Carretas	8,174	82,163	17,728	0,109	4,36
Estibas	8,943	82,371	17,143	0,486	4,47
JBB	9,050	75,072	20,422	4,506	6,21
MRU- con MDF	7,617	78,911	20,041	1,048	4,36

Source: the authors.

The pH was moderately acidic for all the samples evaluated, which can affect its use because in contact with metals it can corrode (IDAE, 2007).

The calorific value of the MRU evaluated was around 17225 kJ/kg and 18430 kJ/kg, as shown in Table 5, values that correspond to the MRU with MDF and the wood coming from Mobiliario, respectively.

Table 5. Poder Calorífico de las diferentes muestras

Muestra	Poder calorífico superior (kJ/kg)
Furniture	18430
Wagons	17500
Pallets	17565
JBB	16065
MRU- with MDF	17225

Source: the authors.

The values obtained are close to the biomasses used for gasification, such as the bagasse of the wet cane and the almond hulls, as shown in Figure 4.

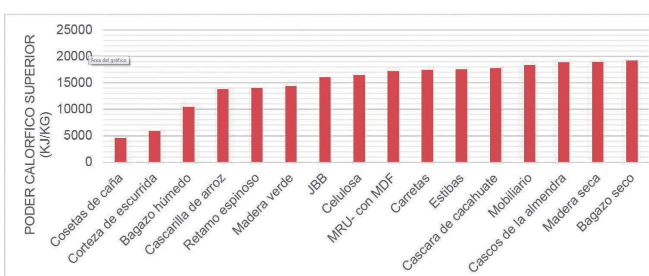

Figure 4. The higher calorific value of different biomasses and those studied
Source: adapted from Serrato and Lesmes (2016).

From the weight loss curves (TGA) and those corresponding to its derivative with respect to time (DTG), the temperature range in which the mass loss was maximum was determined.

In the TGA curve for the Furniture sample (Figure 5) it is observed that the temperature of thermal degradation is between 230 ºC and 390 ºC. The DTG curve shows that the resistance to oxidation is decreasing between 230 ºC and 400 ºC, where the greatest weight loss occurs with a percentage of 64.12 %.

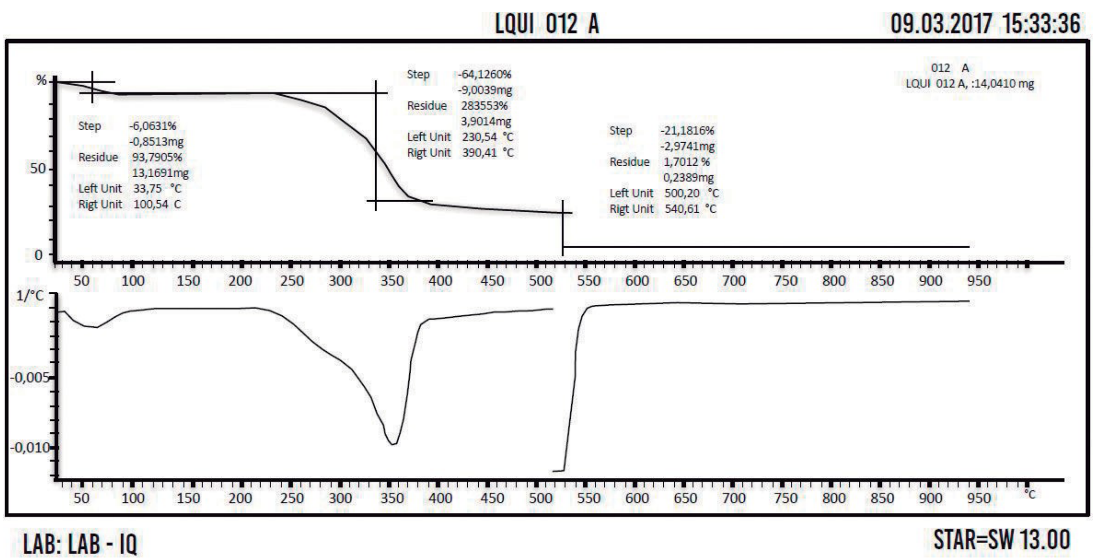

Figure 5. C TGA and DTG curve for the furniture sample
Source: the authors.

For the sample of the MRU from carts, the TGA curve (Figure 6) shows that the temperature of thermal degradation is between 230 ºC and 390 ºC, this curve is very similar to that obtained in the furniture sample. This temperature range presents the greatest weight loss with a percentage of 68.1 %.

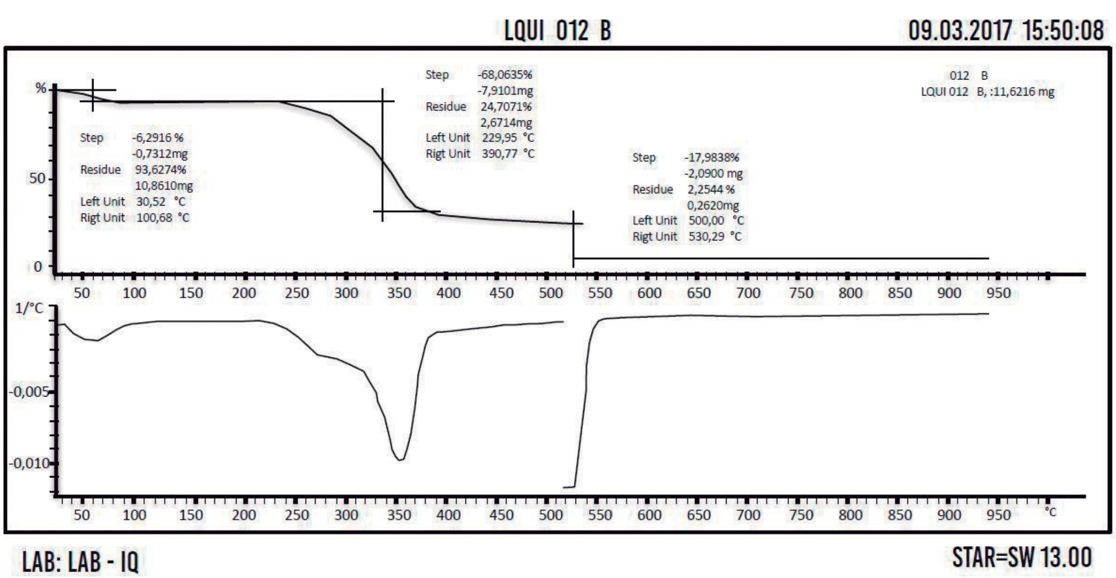

Figure 6. TGA and DTG curve for the cart sample
Source: the authors.

In the TGA curve for the Pallet sample (Figure 7) it is observed that the temperature of thermal degradation is between 230 ºC and 390 ºC. The weight loss starts around 230 ºC and ends after exceeding 350 ºC, very similar to the previous samples. This temperature range presents the greatest weight loss with a percentage of 68.1 %.

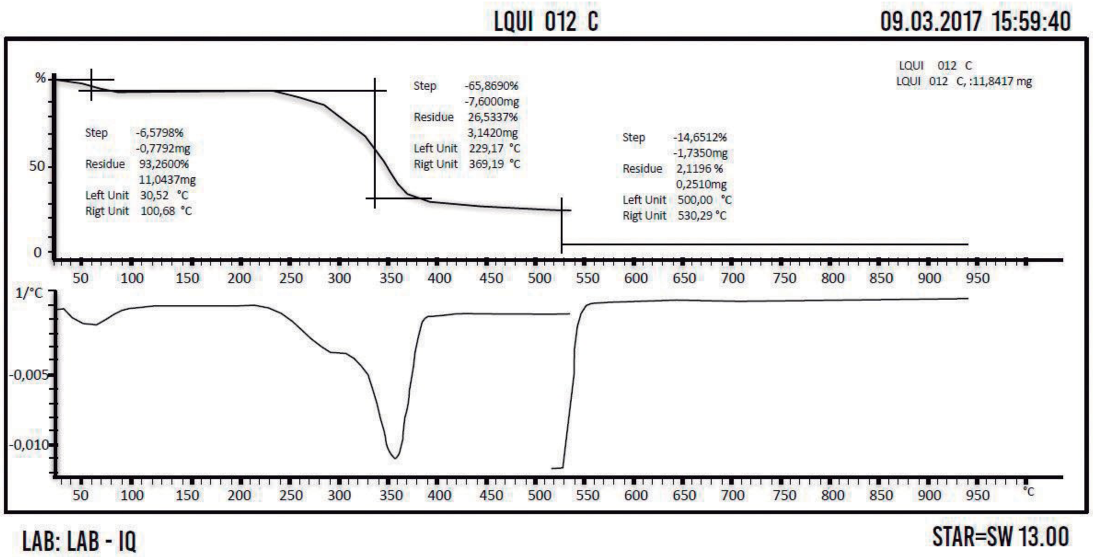

Figure 7. TGA and DTG curve for the sample of pallets
Source: the authors.

For the sample of the JBB wood mixture, the TGA curve (Figure 8) can be observed that the temperature of thermal degradation is between 210 ºC and 390 ºC, this curve is very similar to that obtained in the previous samples due to the origin of all wood biomass. This temperature range presents the greatest weight loss with a percentage of 61.87 %.

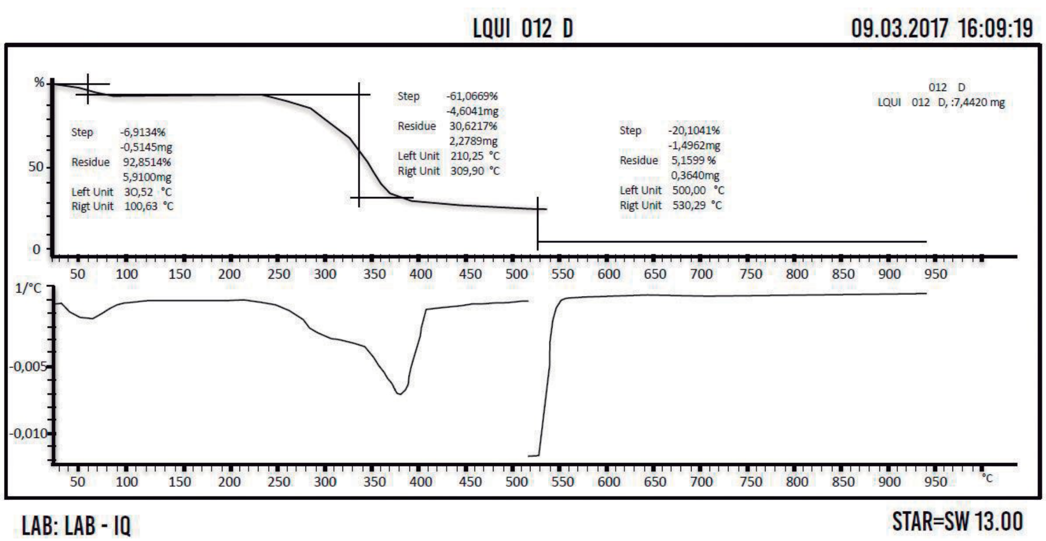

Figure 8. TGA and DTG curve for the JBB sample
Source: the authors.

In the TGA curve for the Stowage sample (Figure 9) it is observed that the temperature of thermal degradation is between 234 ºC and 390 ºC, very similar to the previous samples. This temperature range presents the highest weight loss with a percentage of 62 %.

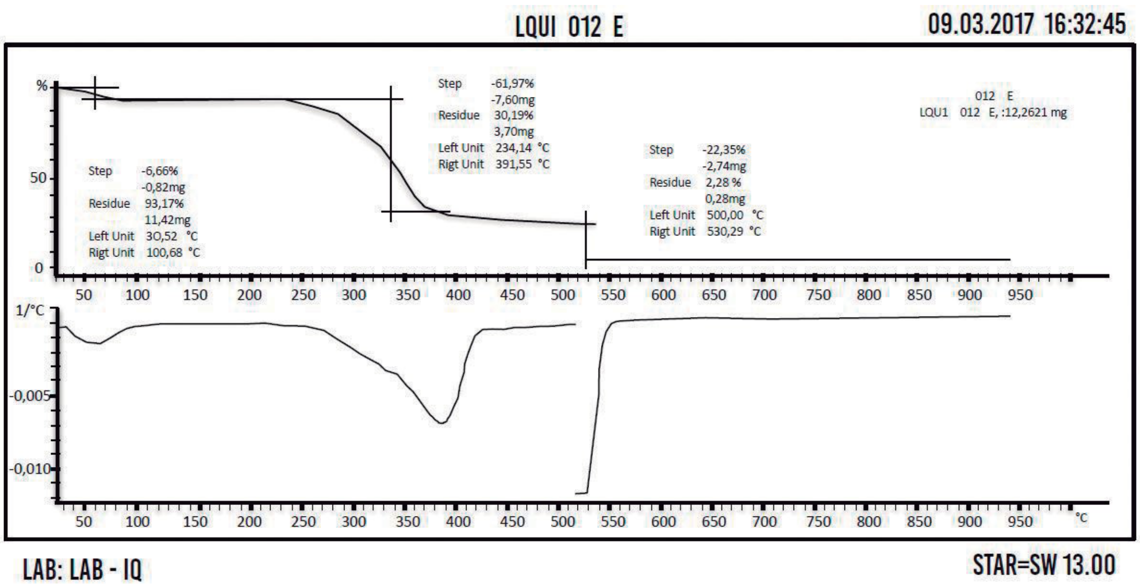

Figure 9. TGA curve and DTG for the sample of MRU with MDF
Source: the authors.

In Figure 10 we can observe the variation of the synthesis gas concentration during the heating period of the system (inputs 1 and 2) and during the generation of electrical energy (inputs 3 and 4).

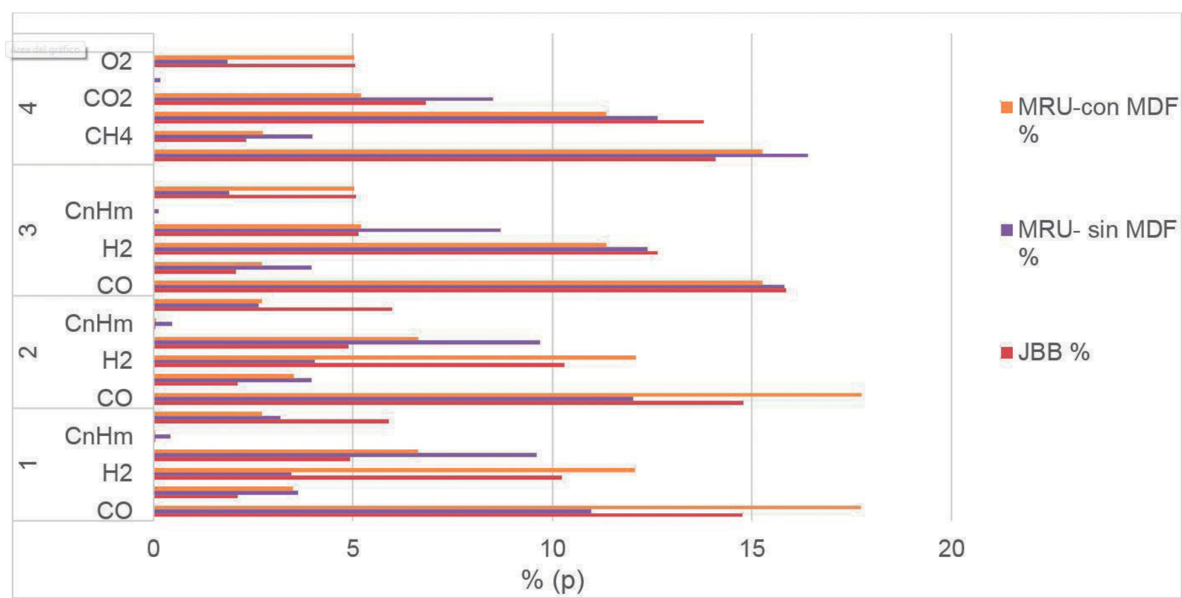

Figure 10. Variation of synthesis gas concentration
Source: the authors.

The generation of methane was similar for the three types of biomass, around 3 %, being higher for the MRU without MDF with an average of 3.88 %. The composition of H2 is around 9.8 %, being higher for the JBB sample. For the CO the composition was around 15 %, being higher for the MRU with MDF with 16.5 % and of CO_2 for MRU without MDF with 9 %.

The Lower Calorific Power (PCI) of the synthesis gas shows lower values than the biomass used in the synthesis gas generation, which agrees with that reported by the literature. The lowest PCI obtained was for the JBB mixture, 936.5 kcal/m^3, followed by the MRU-without MDF was 1003.75 kcal/m^3, and with a higher PCI the MRU-with MDF, 1069.5 kcal/m^3.

Heating ramp

In Figure 11 it is observed that with respect to the established baseline, the natural MRU exceeded the restriction temperature having a peak of 895 °C and the reduction temperature with a peak of 584 °C. On the other hand, the artificial MRU was in the process of heating above the baseline temperatures and then remained below it. Additionally, it is observed that, due to the presence of additives such as synthetic resins, water and paraffin did not allow it to reach temperatures above 800 °C.

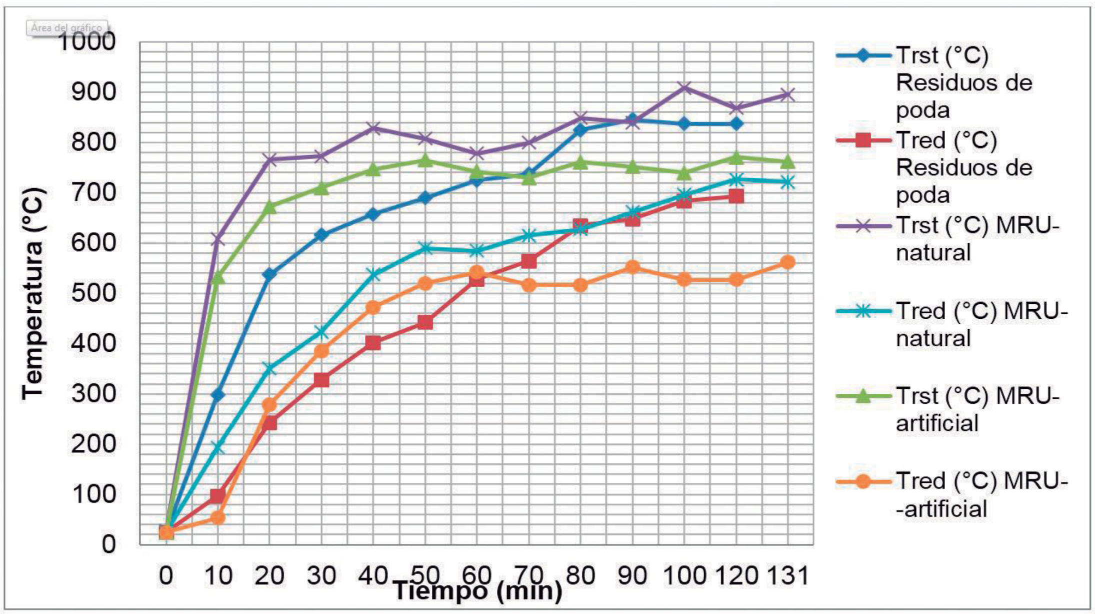

Figure 11. The baseline of operational pruning waste and the natural and artificial urban waste wood (MRU) operating curve. Where Tred corresponds to the Temperature of the reduction zone and Trst to the temperature of the home zone
Source: the authors.

Generated power

The average power generated in the tests with natural MRU and the pruning residues is shown below (see Figure 11). In the tests with MRU-natural, the biomass was compacted in the hopper forming an air bubble, which caused that the feeding of biomass was affected. The alarm was activated by exceeding the maximum temperature (1055 °C), which caused the emergency shutdown of the equipment. In the MRU-artificial tests, it was not possible to generate electric power because during the tests a lot of tar was produced, and the filter saturated in less than 30 minutes, so the governors got dirty and did not work properly.

Biomass consumed per kWh generated

The consumption of biomass per kWh generated was determined, as shown in Table 6, with the highest consumption by pruning waste with 0.33 kg/kWh and for the natural MRU of 0.12 kg/kWh, values that they are below the 1.2 kg/kWh set by the manufacturer.

Table 6. Consumption of biomass per kWh generated

Type of biomass	Biomass consumed (kg)	The energy produced (kWh)	Kg/kWh
MRU-natural	29,84	244	0,12
MRU-artificial	34,95	-	-
Waste pruning	63,54	193	0,33

Source. the authors.

Energy performance

The overall energy performance of the generation system was higher for the natural MRU with 60 %, compared to 56 % with the pruning residues (Figure 12).

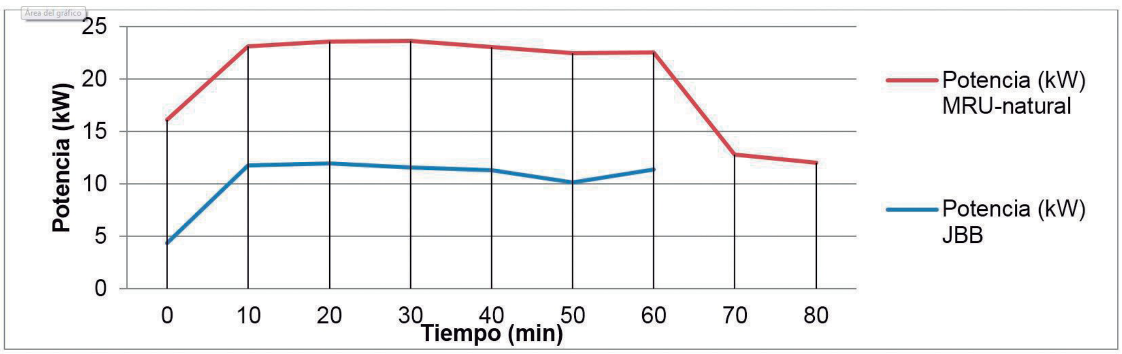

Figure 12. Average power generated
Source. the authors.

Economic aspects

Additionally, the cost of generating the kWh with the pruning residues and the MRU was determined. Table 7 shows the generation costs using different fuels. In accordance with what was established by the manufacturer, we observed that the generation costs determined for the pruning residues and the MRU are within the established range.

Table 7. Comparison of generation prices

Gas	Generation cost (USD$)
Diesel*	$0,35 - $0,70/kWh
Gasoline*	$0,50 - $1,00/kWh
Biomass *	$0,10 - $0,30/kWh
MRU	$0,10 - $0,20/kWh
Waste pruning	$0,10 - $0,20/kWh

Source: adapted from (All Power Labs, 2014).

The energy potential of the MRU of the city of Bogotá

According to a study by the UAESP, for the year 2016, the city according to the cleaning operators on average 6 % (138,100 t/year = 378 t/day) of urban solid waste corresponds to wood. In order to have an estimate of the amount of urban waste wood available for the gasification process, an estimated per capita production of 0.8 kg/day was identified for the year 2013, equivalent to 0.29 t/year, and taking into account population growth for the District of Bogotá until 2027 (Mayor Mayor of Bogotá, 2014), the volume of waste was determined. With an average calorific value of 19000 kJ/kg (Viloria, 2013) for dry wood, taking into account that the plant will have an operating regime of 8,000 hours/year and the performance between the chemical energy contained in biomass and electric power obtained in this type of power plants is usually 25 % (Toval, 2014), and that the percentage of waste of biomass of 20 %, we have that Energy/year available is shown in Table 8.

Tabla 8. Determination of available energy per year according to population growth

Year	Population	% increase	Ton RSU/year	Ton MRU/year	MJ	Energy available per year (MWh)	Power (kW)
2013	7.674.971	1,36%	2.225.741	133.544	570.903	1,59E+02	19,82
2014	7.777.815	1,34%	2.255.566	135.334	578.553	1,61E+02	20,09
2015	7.879.705	1,31%	2.285.114	137.107	586.132	1,63E+02	20,35
2016	7.980.565	1,28%	2.314.364	138.862	593.634	1,65E+02	20,61
2017	8.081.120	1,26%	2.343.525	140.611	601.114	1,67E+02	20,87
2018	8.181.326	1,24%	2.372.584	142.355	608.568	1,69E+02	21,13
2019	8.281.138	1,22%	2.401.530	144.092	615.992	1,71E+02	21,39
2020	8.380.512	1,20%	2.430.348	145.821	623.384	1,73E+02	21,65
2021	8.409.005	0,34%	2.438.612	146.317	625.504	1,74E+02	21,72
2022	8.488.891	0,95%	2.461.778	147.707	631.446	1,75E+02	21,93
2023	8.566.989	0,92%	2.484.427	149.066	637.255	1,77E+02	22,13
2024	8.643.235	0,89%	2.506.538	150.392	642.927	1,79E+02	22,32
2025	8.717.567	0,86%	2.528.094	151.686	648.456	1,80E+02	22,52
2026	8.789.922	0,83%	2.549.078	152.945	653.838	1,82E+02	22,70
2027	8.860.242	0,80%	2.569.470	154.168	659.069	1,83E+02	22,88

Source. the authors.

Conclusions

The physicochemical characterization of the MRU from natural and artificial wood allows us to conclude that:

• When presenting a moisture content of less than 10 % there is a risk of reaching excessively high temperatures in the chimney, benefiting the formation of slag and the fusion of the ash, an ash content of less than 5 %, it is favorable since it will not be trained of scum.

• A moderately acidic pH can affect its use because in contact with metals it can corrode.

• With a percentage of exploitation so low, around 25 %, it is recommended to evaluate another technology that allows greater flexibility in terms of particle size.

• The content of volatile matter was greater than the recommended 10 %, therefore, for this type of biomass, it is more advisable to use it in gasifiers of moving the bed in the parallel current.

• The presence of nitrogen in the sample of MRU with MDF, (artificial wood) but low can contribute to the formation of nitrogen oxides (NOx) that favor the formation of acid rain.

On the other hand, in the generation of energy, it was observed that the natural MRU shows a warming ramp faster than that presented by the pruning residues and the artificial MRU, which is due to the low ash content and will be reflected at a higher operating temperature, and higher gas quality.

The biomass consumption per kWh generated was 0.33 kg/kWh, which shows that the MRU decomposes more easily than the pruning waste, with a value of 0.12 kg/kWh.

The power generated was around 12 kW, a value very close to that generated by the pruning waste, reaching a peak of 12.8 kW. The artificial MRU presents a high generation of tars, which can be propitiated by the temperatures in the restriction zone producing a partial conversion of the tars and increasing the concentration of heavy pitches. As a result, rapid saturation of the filter medium occurred and therefore the effect on the operation of the motor governor.

According to the technical evaluation, it is concluded that the Power Pallet ® PP20 technology is not the most suitable for the use of the MRU, due to the restrictions of the particle size and the cleaning of the synthesis gas. Within the technological aspects, it is highlighted that this type of technology is found in TRL 8, which is a complete and certified system through tests and demonstrations. However, in the geographical and climatic conditions, in addition to the type of biomass used and the continuous operation, it is necessary to carry out a thorough evaluation of its influence and evaluate other technologies on a larger scale.

According to the estimated annual average amount of urban residual wood of 144,667 tons, the available energy will be 1.72E + 02 MWh per year, therefore, the maximum power that could be installed by the District would be 20 kWe. Although this potential is low compared to other types of biomass, it is an environmentally viable alternative that will allow the valorization and reuse of the MRU.

References

Alcadía Mayor de Bogotá. (2014). *Demografía, población y diversidad.* Bogota, Colombia. Recuperado de: http://www.sdp.gov.co/portal/page/portal/PortalSDP/Noticias2014/SDP_realiza_lanzamiento_de_su_coleccion_de_libros_Bogota_Hum/02.DEMOGRAFIA.pdf

All Power Labs. (2014). *Power pallet operation maual*. Recuperado de: http://www.allpowerlabs.com/products/20kw-power-pallets

Aruna, P.B., Laarman, J. G., Araman, P., Coulter, E., y Cubbage, F. (1997). Used pallets as a source of pellet fuel: Current industry status. *Forest Products Journal, 47*(9), 51–56.

Bratkovich, S., Bowyer, J., Lindburg, A., y Fernholz, K. (2009). *Reclaiming lumber products from waste wood.* Minneapolis. Recuperado de http://www.dovetailinc.org/report_pdfs/2009/dovetailreclaim0109.pdf

Fernández, K., Martínez, D., y López, M. (2015). *Revisión y análisis de las asociaciones de recicladores en Bogotá diseñando una estrategia de negocio para la valorización y reutilización de residuos sólidos.* (Tesis de pregrado). Universidad del Rosario, Bogotá, Colombia. Recuperado de: http://repository.urosario.edu.co/bitstream/handle/10336/10445/1010204773-2015.pdf?sequence=10

Fonseca González, N.E (2003). *Estado del arte del uso del gas de gasificación termoquímica de biomasa (GG), en motores de combustión interna alternativos.* (Tesis de doctorado). Universidad Politécnica de Madrid. Madrid, España. Recuperado de: http://oa.upm.es/10905/

García Barriga, H. (1968). *Árboles de la Sabana de Bogotá. Revista de La Academia Colombiana de Ciencias Exactas, Físicas Y Naturales, 13*(50), 273–277.

Held, J. (2012). *Gasification - Status and technology*; Rapport SGC 240, (June), 48. Recuperado de: http://www.sgc.se/ckfinder/userfiles/files/SGC240.pdf

Instituto para la Diversificación y Ahorro de la Energía (IDAE). (2007). *"Biomasa: Gasificación."* Madrid. Recuperado de: http://www.idae.es/publicaciones/biomasa-gasificacion

IDAE, y ESCAN, S. A. (2008). *Biomasa: Industria*. Madrid. Retrieved from http://www.idae.es/uploads/documentos/documentos_10980_Biomasa_industria_A2008_A_402485e2.pdf

Jaramillo Henao, G., y Zapata Márquez, L. M. (2008). *Aprovechamiento de los residuos sólidos orgánicos en Colombia.* (Tesis de Especialización). Universidad de Antioquia, Medellín, Colombia. Recuperado de: http://tesis.udea.edu.co/handle/10495/45

Ministerio de Vivienda Ciudad y territorio. (2015). *Guía para la formulación, implementación, evaluación, seguimiento, control y actualización de los PGIRS*. Bogota, Colombia. Recuperado de: http://www.minvivienda.gov.co/Documents/ViceministerioAgua/PGIRS/PGIRS de Segunda Generación/Guía para la formulación, implementación, evaluación, seguimiento, control y actualización de los PGIRS.pdf

Moratorio, D., Rocco, I., y Castelli, M. (2012). Conversión de residuos sólidos urbanos en energía. *Memoria de Trabajos de Difusión Científica Y Técnica, 10*, 115–126. Recuperado de: http://www.um.edu.uy/docs/10_conversion_de_residuos_solidos_urbanos-en_energia.pdf

OpEPA. (2016). *Árboles de Bogotá y sus arbustos.* Retrieved April 15, 2017, from http://www.opepa.org/index.php?option=comcontent&task=category&sectionid=10&id=82&Itemid=30

Primadera S.A.S. (2017). *Madera urbana, el renacer de la madera.* Recuperado de: http://www.primadera.com/maderaurbana

Pujoldevall Sánchez de Toledo, O. (2015). *Diseño y construcción de un sistema de generación eléctrica mediante gasificación de biomasa.* (Tesis de licenciatura). Universitat Politécnica de Cataluña (UPC). Recuperado de: http://upcommons.upc.edu/bitstream/handle/2099.1/25234/TFG.pdf?sequence=1

Rocha O, J., Vesga, N., y Pinto, S. (2011). *Evaluación exergética del proceso de extracción de aceite de palma africana*. Universidad Industrial de Snatander.

Serrato Monroy, C. C., y Lesmes Cepeda, V. (2016). *Metodología para el Cálculo de Energía Extraida a Partir de Biomasa en el Departamento de Cundinamarca.* (Tesis de pregrado). Universidad Distrital Francisco José De Caldas, Bogotá Colombia.

Superintendencia de Servicios Públicos Domiciliarios. (2015). *Disposición Final de Residuos Sólidos Informe Nacional Elaborado 2015.* Bogota, Colombia. Recuperado de: http://www.superservicios.gov.co/content/download/10760/88380

Toval Martinez, I. (2014). *Estudio de viabilidad, dimensionamiento e instalación eléctrica en una planta de Cogeneración a partir de gasificación de biomasa de 2 MW.* Universidad Politecnica de Cartagena. Recuperado de: http://repositorio.upct.es/bitstream/handle/10317/4003/pfc5721.pdf?sequence=1

UAESP. (2011). C*aracterización de los residuos sólidos institucionales, pequeños productores generados en la ciudad de Bogotá D.C*. Bogota D.C. Recuperado de http://www.uaesp.gov.co/uaesp_jo/images/documentos/Caracterizacion/institucionales_02-29-2012.pdf

Viloria, J. R. (2013). *Energías renovables. Lo que hay que saber* (2a edición). Madrid: Ediciones Paraninfo, S.A. Recuperado de: https://books.google.com/books?id=yKh2AgAAQBAJ&pgis=1