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The Available Waste-to-energy Potential from Agricultural Wastes in the Department of Córdoba, Colombia

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ABSTRACT

There is a large potential for biomass-based renewable energy production Colombia which mostly remains untapped, accounting for a marginal 0.8% of the electricity production. Moreover, Córdoba is a department with important developments in agriculture and agroindustry, where significant amounts of biomass wastes are generated. In total, these wastes have a yearly energy potential of 548 for the use of anaerobic digestion, and 1159 GWh per year using direct combustion. These energy potentials can yield 126 GWh/year of electricity using anaerobic digestion, or 260 GWh/year using direct combustion (i.e. 9 to 18% of the current electricity demand). However, power generation systems based on direct combustion for biomass wastes are economically feasible only for the lower investment costs available in the market, while anaerobic digestion is feasible for the low and average investment costs available in the market. Moreover, the biogas potential is equivalent to 1.4 times the energy demand required to replace firewood for cooking in 32% of the department homes that use firewood. More investigation is needed to more accurately define the potentialities of biomass wastes for energy applications in the department, for more effective promotion of its implementation.

Keywords: Renewable Energy, Biomass Waste, Waste-to-energy Technologies, Bioelectricity
JEL Classifications: O, Q

1. INTRODUCTION

Energy is essential for economic development and to guarantee adequate life quality standards as was acknowledge in the sustainable development goals (i.e. SDG 7) (United Nations, 2015). However, the current energy demand, which is expected to increase by 48% by 2040 (Avcıoğlu et al., 2019)., is primarily supported by fossil fuels.

Colombia has a large untapped biomass-based energy potential (Gómez-Navarro and Ribó-Pérez, 2018). However, it is hardly exploited supporting a marginal 0.8% of the power capacity installed for power generation in the country (Ramírez et al., 2018), and a limited development is foreseen in the medium to long term future (Cabello et al., 2019). Renewable energy studies mainly discuss the application of either solar, wind, or hydraulic projects (Robles et al., 2017), frequently failing to address the potentialities of biomass for potential applications like power generation, biofuel production, as cooking fuel, etc. To meet the 20% reduction target in 2030 of greenhouse gas (GHG) emissions,ssit is of the essence to widespread the implementation of biomass energy applications.

In particular, the department of Córdoba faces the challenge of diversifying its energy mix towards more sustainable development. There are different activities with important contributions to the gross domestic product of the department (e.g. agriculture, manufacturing industry, construction, and telecommunications) that requires a stable supply of energy for their development and growth. In the department, the electric coverage is high with 98%, although in rural areas there is 5% of the population with no coverage and others with a lower quality service. Additionally, 32.3% of the 466,615 houses cook with firewood, which increases to 66.3% in rural areas. However, even though the use of biomass can help to address this situation, there are a few renewable energy-based projects only focusing on solar energy (DANE, 2018; UNDP, 2019).

Córdoba is a department with significant development of agricultural activities that account for 10.6% of the departmental GDP. Agricultural wastes and the agroindustrial waste from processing agricultural products have a significant potential for biomass-based energy systems (Sagastume et al., 2020). Therefore, given the need to diversify the energy mix in Córdoba, which can be aided with biomass sources that are currently a waste from agricultural activities, this study aims at defining the bioenergy potential of agricultural and agroindustrial wastes in the department.

2. MATERIALS AND METHODS

Following the materials and methods used to calculate the bioenergy potential of agricultural biomass wastes are described.

2.1. Energy Demand in Córdoba

The department of Córdoba consumed between 1,477 and 1,426 between 2016 and 2017 (Ramírez et al., 2018). Additionally, the department consumed around 174 million liters of gasoline and 144 million liters of diesel in 2018 for transport (MINMINAS, 2018a, 2018b). Moreover, firewood demand for cooking fuel averages a daily consumption of 14.5 kg per house in rural areas of the department (i.e. a per capita of 3.3 kg/day), causing different health issues (Sanchez and Galvis, 2016). Indoor air pollution from cooking with traditional solid biomass fuels is a significant issue affecting 2.6 billion people in emerging economies (International Energy Agency, 2020). Given that 32.3% of the 466,615 homes in the department using firewood, and estimated 790,259 t of firewood (i.e. 4,105 GWh/year considering a heating value of 18.7 MJ/kg (Pérez et al., 2019)), are demanded per year. Open fire systems has thermal efficiencies between 1 and 17% (Carranza and Gutiérrez, 2012). In Colombia, the average thermal efficiency of 4.8% was experimentally measured (Consorcio Estrategia Rural Sostenible, 2019), which result in useful energy of 197 GWh/year obtained from the firewood for cooking.

2.2. Agriculture in Córdoba

In Córdoba, agricultural production is mainly focused on eight crops as shown in Table 1.

In total, the main crops account for 90% of the agricultural production in the department. Particularly, cassava, plantain, maize, and yam account for almost 80% of the total production, and rice, coconut, cotton, and oil palm account for a lower 12.5%.

The wastes factors and properties of the different biomass sources are depicted in Table 2.

Occasionally, agricultural wastes are used as a source of moisture and nutrients to the soil, prevent the erosion of soil, etc. (Leal et al., 2013), or as animal feed. Particularly, the stalk and leaves waste of yam and the pseudostem of plantain are used as a source of moisture and nutrients to the soil and are thus not stressed in this study.

2.3. Biomass to Energy Potential

In this study, the energy potential is calculated based on the availability of biomass and its properties considering direct combustion and anaerobic digestion as potential technologies to exploit biomass sources.

2.3.1. Direct combustion

Direct combustion is recommended for biomass sources with less than 50%. The energy potential from a given amount of biomass from a defined source (e.g. plantain wastes), considering direct combustion depends on its heating value (Sagastume et al., 2020):

$$W_{E.DCi}=M_i \cdot LHWw.b_i \tag{1}$$

Where $W_{E.DCi}$ stand for the energy potential of the

i-est biomass source using direct combustion (in GWh), M_i is the biomass available from the i-est source (in million t), and $LHWw.b_i$ stand for the low heating value of the i-est biomass source on a wet basis (GWh/million t).

The LHV available in specialized literature for the different biomass sources discussed in this study were considered. When the high heating value (HHV) was available rather than the LHV, the LHV was calculated using the moisture content (MC) as (Boundy et al., 2011):

$$LHV_{w.b}=HHV_{d.b}\cdot(1-MC)-2.447\cdot MC \tag{2}$$

where w.b stands for a wet basis, while d.b stands for a dry basis.

The total bioenergy potential from the biomass wastes available for direct combustion can be calculated as:

Table 1: Agricultural production in Córdoba

Crop	2013	2014	2015	2016	Average	Production (%)
	(t/year)					
Cassava	317,434	295,437	330,370	300,685	310,982	26.9
Plantain	229,844	232,201	224,848	257,635	236,132	20.4
Maize	247,216	220,994	187,193	222,638	219,510	19.0
Yam	113,999	120,515	111,559	161,023	126,774	11.0
Rice	93,458	88,907	79,724	84,889	86,745	7.5
Coconut	29,949	29,538	28,102	23,861	27,863	2.4
Cotton	29,949	29,538	28,102	23,861	27,863	2.4
Oil palm	984	995	1,882	5,907	2,442	0.2
Others	110,499	110,836	94,305	152,644	117,071	10.1
Total	1,173,332	1,128,961	1,086,085	1,233,143	1,155,380	100.0

Source: Ministerio de Agricultura y Desarrollo Rural. 2018a, 2018b

Table 2: Wastes factors and properties of biomass sources

Crop	Waste	MC (%)	X_C (%)	X_{HC} (%)	X_L (%)	$VS_{d.b.}$ (%)	LHV (MJ/kg)	HHV (MJ/kg)	Waste factor ($t/t_{product}$)	Reference
Plantain	Rachis	93.6	53	17	16	79.1	-	14.39	0.16	(Sagastume et al., 2020)
	Pseudo-stem	90.0	54	16	21	88.8	-	15.50	3.00	
	Waste plantain	79.0	4	4	4	89.7	-	17.15	0.15	
	Peels	89.1	12	13	2	86.3	-	17.15	0.27	
Rice	Straw	11.3	32	36	22	79.7	13.86	-	2.35	
	Husk	23.0	35	25	20	69.1	15.07	-	0.20	
Cassava	Stalks	15.5	23	29	22	79.9	13.38	-	0.09	
	Rhizome	8.3	34	17	28	77.0	10.61	-	0.49	
	Peel	70.0	14	23	11	74.5	3.66	17.90	0.15	
	Bagasse	85.0	16	5	3	81.7	0.21	15.27	0.90	
Maize	Stubble	7.9	45	25	15	73.0	14.35	-	0.93	
	Cob	6.7	28	26	19	74.2	14.18	-	0.27	
	Stover	7.0	40	25	14	75.3	15.96	-	0.21	
Oil palm	Shell	7.0	21	23	51	83.6	16.69	-	0.22	
	Fiber	3.5	43	18	25	73*	17.88	-	0.63	
	Empty bunches	4.7	42	13	24	74*	18.64	-	1.06	
	POME	87.1	11	7	42	6*	-	-	0.80	
Cotton	Stalks	7.0	38	32	21	69*	15.85	17.23	1.77	(Shah et al., 2019; Ullah et al., 2015)
Yam	Stalk and leaves	-	-	-	-	-	-	-	0.09	(Astudillo et al., 2015; Ibeto et al., 2016; Jekayinfa and Omisakin, 2005)
	Waste yam	12.0	40	30	7	58	-	19.44	0.07	
Coconut	Husk	10.0	39	20	37	73*	18.62	20.95	0.34	(Bhatnagar et al., 2010; Rocha et al., 2017; Wang and Sarkar, 2018)
	Shell	12.9	42	21	39	64*	15.07	17.66	0.18	(Chen and Kuo, 2010; Sarki et al., 2011)

*VS on wet basis

$$W_{E.DC} = \sum_{1}^{i} W_{E.DC_i} \tag{3}$$

Where $W_{E.DC}$ stands for the total bioenergy potential from the biomass wastes available for direct combustion (GWh).

2.3.2. Anaerobic digestion

Anaerobic digestion is adequate for biomass sources with moistures higher than 50%. Although it can be used with any biomass source, regardless of its moisture. The process of anaerobic digestion is developed in four steps:

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis.

The product of this process is biogas, which is a mix of CH_4 (50 to 70%) and CO_2 (30 to 50%), with small traces of other gases. Anaerobic digestion is developed in the absence of oxygen in reactors design to this end. Biogas is a fuel adequate for heat and electricity conversion. The digestate resulting from the digestion process is a valuable byproduct that can be applied as fertilizer or for soil amendment (Mayer et al., 2019).

For lignocellulosic biomass sources, the biomethane potential (i.e. the fraction of CH_4 in the biogas) can be calculated as a function of its cellulose, hemicellulose, and lignin content as (Thomsen et al., 2014):

$$BMP_i = 378 \cdot x_{Ci} + 354 \cdot x_{Hi} - 194 \cdot x_{Li} + 313 \cdot x_{Ri} \tag{4}$$

Where BMP_i stands for the biochemical methane potential of the i-est source of biomass $\left(\frac{L}{kg_{VS}}\right)$, and x_{Ci}, x_{Hi}, x_{Li} and x_{Ri} stand for the fraction of cellulose, hemicellulose, lignin, and the remaining biomass constituents of the i-est biomass source respectively.

The volume of biomethane that might be technically produced (i.e. technical methane potential [TMP]) depends on the energy demand to preheat feedstock and the heat loss during heat (that can be considered as 10% of the energy) (Wang et al., 2018):

$$TMP_i = BMP_i - \frac{\sum_{1}^{j} 1.1 \cdot M_i \cdot c_P \cdot (T_R - T_o)}{LHV_{CH_4}} \tag{5}$$

Were TMP_i stands for the technical methane potential of the i-est biomass waste ($m^3/t_{biomass}$), C_p is the specific heat of the feedstock (Considered equal to 4.2 kJ/kg, T_R is the operational temperature of the digester (°C), T_o is the ambient temperature (°C), and LHV_{CH4} stands for the low heating value of CH_4 (kJ/m^3)

The energy potential of the i-est biomass source considering anaerobic digestion can be calculated as (Sagastume et al., 2020):

$$W_{E.ADi} = M_i \cdot TMP_i \cdot LHV_{CH4} \tag{6}$$

Where $W_{E.ADi}$ stands for the bioenergy potential of the i-est biomass waste available for the anaerobic digestion (GWh)

The total bioenergy potential of the biomass wastes available for anaerobic digestion can be calculated as:

$$W_{E.AD} = \sum_{1}^{i} W_{E.AD_i} \tag{7}$$

2.3.3. Potential electricity production

The potential electricity conversion is calculated based on electricity efficiencies of 28% and 30% for direct combustion and anaerobic digestion respectively (Pöschl et al., 2010). Additionally, it is considered that 20% of the electricity is used for the self-demand of the direct combustion or the anaerobic digestion systems (Dong et al., 2018).

The electric potential is then calculated as:

$$W(elect.X_i)=0.8\cdot(M_i\cdot W_{E.Xi}\ \eta_{elect}) \quad (8)$$

Where $W(elect.X_i)$ stand for the electricity potential from direct combustion (i.e. for X = DC) or anaerobic digestion (i.e. for X = AD) for biomass waste i (GWh), similarly $W_{E.Xi}$ is the bioenergy potential from direct combustion (i.e. for X = DC) or anaerobic digestion (i.e. for X = AD) for the i-est biomass waste, which is calculated with equations 3 or 7, and η_{elect} is the electricity efficiency

In the total electricity of the different biomass available is then calculated as:

$$W_{elect.X} = \sum_{1}^{i} W_{elect.X_i} \quad (9)$$

Where $W_{elect.X}$ the electric potential available from the biomass wastes using direct combustion (i.e. for X = DC) or anaerobic digestion (i.e. for X = AD).

Since either direct combustion or anaerobic digestion can be used to cogenerate heat, the heat potential from the i-est biomass source is calculated as:

$$W_{heat.Xi}=W_{E.Xi}\ \eta_{thermal} \quad (10)$$

Where $W_{heat.Xi}$ is the heat conversion potential from the i-est biomass waste available for direct combustion (i.e. for X = DC) or anaerobic digestion (i.e. for X = AD) (GWh), and $\eta_{thermal}$ stands for the thermal efficiency of the technology.

The total heat potential is calculated as:

$$W_{heat.X} = \sum_{1}^{i} W_{heat.X_i} \quad (11)$$

Where $W_{heat.X}$ is the heat potential of the biomass wastes available for direct combustion (i.e. for X = DC) or anaerobic digestion (i.e. for X = AD) in (GWh).

2.4. Economic Assessment

To assess the potential economic introduction of either direct combustion or anaerobic digestion systems an assessment is developed. Towards a comprehensive economic evaluation, the net present value NPV and the internal rate of return (IRR) are used. The IRR is the discount rate, which makes 0 the NPV.

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \quad (12)$$

$$\sum_{t=0}^{N} \frac{C_t}{(1+IRR)^t} = 0 \quad (13)$$

Where:
i – Financial discount rate (%)
t – time (year)
C_t – Net cash flow at time t (USD/year)
N – Total time periods (year).

The capital cost (CAPEX) and the operational costs (OPEX) considered are depicted in Table 3.

Fixed OPEX fixed for biogas systems for power generation are included in OPEX variable. For the assessment, the selling price of electricity is considered equal to 0.1 USD/kWh. Moreover, firewood costs 3.3% of the minimum monthly legal salary (i.e. around 8 USD per month), requiring 14 h a month to get the firewood.

2.5. Biomass Available from the Different Crops

The availability of biomass wastes for bioenergy applications in agriculture depends on factors like harvesting procedures and agricultural practices. On the other hand, although agroindustrial wastes are readily available for energy applications, the production of wastes, in this case, depends on the fraction of the agricultural production processed in agroindustry (Table 4).

Some crops like rice, oil palm, and cotton need to be processed in agroindustry to obtain commercial products, while others (e.g. cassava, plantain, and coconut) can be directly marketed after harvesting or processed in the agroindustry to produce other products.

The production of agricultural products and the biomass wastes available from agriculture and agroindustry are depicted in Figure 1.

The average production of agricultural products of 1,155,380 tons results in the generation of an estimated 1,947,795 tons of wastes, of which 238,156 tons are available for energy applications in agriculture and 242,668 tons are available from agroindustry. Cassava with 48 % account for the highest generation of available waste, followed by plantain, maize, and cotton with 21%, 12%, and 10% respectively. The remaining crops have a marginal contribution of less than 3%.

3. RESULTS AND DISCUSSION

The energy potential of agricultural wastes was calculated depending on its characteristics. For biomass wastes with moistures lower than 50% the direct combustion potential was calculated, while the potential from anaerobic digestion was calculated for all of the available biomass sources. The specific energy potential of biomass sources under 50% moisture for direct combustion varies from 660 to 1160 kWh/t. Moreover, for anaerobic digestion 64 and 461 kWh/t. Figure 2 shows the total energy and electrical potentials of the available biomass sources for direct combustion.

Table 3: Capital and operational costs of direct combustion and anaerobic digestion technologies

System	Plant size (MW)	CAPEX (USD/kWe)	OPEX fixed (% of CAPEX)		OPEX variable ($/MWh)		Reference
Power with steam cycle	1–5	5000–10,000	3	6	3	7	(International Finance Corporation, 2017)
	5–10	4000–8000	3	6	3	7	
	10–40	3000–6000	3	6	3	7	
Power with biogas	1–5	3500–6500	-	-	20	40	
Small scale biogas	50*	100–200**	-	-	-	-	(Garfí et al., 2019)

*Refers to input kg/day, **Refers to total capital costs of the project

Table 4: Share of agricultural production processed in agroindustry

Crop	Agroindustry (% of agriculture production)	Reference
Cassava	16	(Sagastume et al., 2020)
Plantain	1	
Maize	-	
Yam	-	
Rice	100	
Coconut	70	(Fondo Emprender, 2018)
Cotton	100	(Sagastume et al., 2020)
Oil palm	100	

In total, the energy potential for the application of direct combustion technologies amounts 1,159 GWh/year, which can yield 250 GWh/year of electricity with adequate technologies. This potential coincides with 18% of the average electricity consumption between 2016 and 2017. However, these residues are scattered throughout the agricultural areas in the department. Additionally, except for some agroindustrial residues, agricultural biomass wastes are stational, making their availability for energy application irregular. Therefore, a more detailed assessment is needed to define the actual availability of biomass wastes for energy applications depending on geographical location and time of the year, to more clearly defines the actual potential to implement direct combustion technologies.

The results show a bioenergy potential for anaerobic digestion technologies accounting for 548 GWh/year, which can yield 126 GWh/year of electricity with adequate technologies. This potential coincides with 9% of the average electricity consumption between 2016 and 2017. However, since these residues are scattered through agricultural areas of the department, a more detailed assessment is needed to more clearly define the actual potential to implement direct combustion technologies.

Following, it is developed the economic assessment of implementing adequate technologies to realize the energy potential identified. It is considering the implementation of biomass plants between 1 and 40 MW for direct combustion, and between 1 and 5 MW for anaerobic digestion. A range of capital costs (i.e. low CAPEX, average CAPEX, and high CAPEX, Table 3) is considered for the different technologies based on the market.

The results show that the implementation of direct combustion technologies economically feasible only for the lowest range of investment costs available in the market. Moreover, for the average

Figure 1: Average agricultural production and biomass wastes availability from 2013 to 2016 (Ministerio de Agricultura y Desarrollo Rural, 2017, 2016)

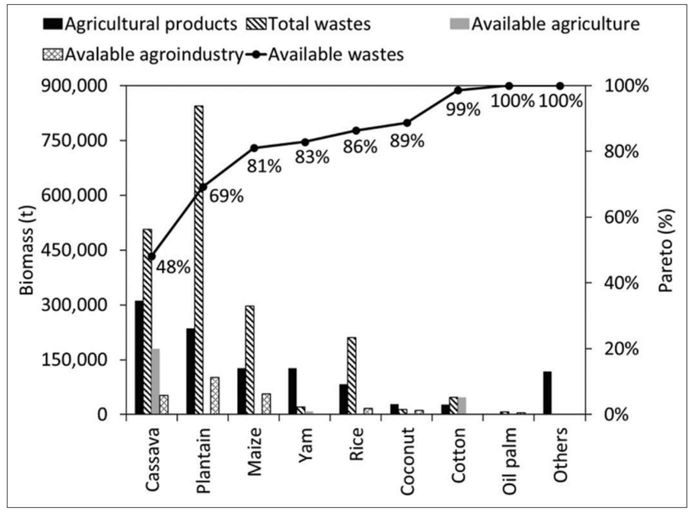
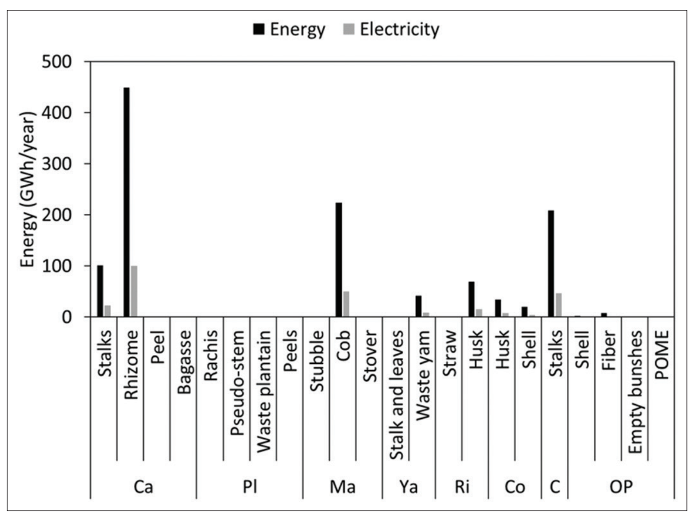


Figure 2: Bioenergy potential from applying direct combustion technologies



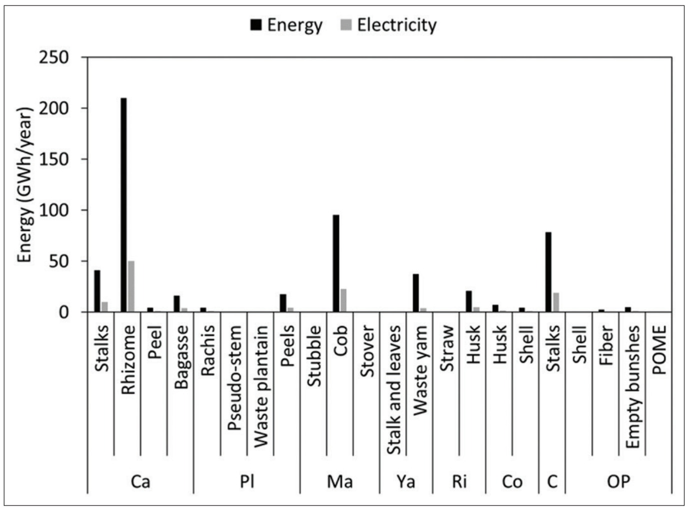
and high CAPEX the implementation is not economically feasible. In the case of anaerobic digestion, it results in a lower NPV as compared to direct combustion, it is economically feasible for the low and the average CAPEX Table 5.

It is important to discuss the potential applications of anaerobic digestion to replace firewood as a cooking fuel in rural areas. Gas stoves using biogas, LPG or natural gas has thermal efficiencies

Table 5: Results of the economic assessment

Technology	Economic indicator	CAPEX		
		Low	Average	High
Direct combustion	NPV (USD)	618,114,639	–169,826,072	–1,118,768,799
	IRR (%)	21.91	3.74	–9.04
Anaerobic digestion	NPV (USD)	53,359,112	11,049,480	–34,765,875
	IRR (%)	17.29%	8.05%	1.27%

Figure 3: Bioenergy potential from applying anaerobic digestion technologies



around 50% (Kurchania et al., 2010; Ltodo et al., 2007; Shen et al., 2018). Therefore, biogas stoves would demand total energy of 394 GWh/year to meet the 197 GWh/year of useful cooking energy demand currently supplied with firewood. The biogas potential identified from agricultural and agroindustrial wastes is (Figure 3) enough to support 1.4 times this demand of biogas. This potential can be increased with the use of manure and other organic wastes not discussed in this study. Small scale biodigesters that can yield from 0.8 to 1.7 m^3/day of biogas (65% CH_4 content) with a daily substrate supply of 50 kg of biomass has been developed in Colombia (Garfí et al., 2019). These biodigesters are enough to support the average cooking energy demand for homes using firewood.

4. CONCLUSION

The bioenergy potential from agricultural and agroindustrial biomass wastes can support from 9 to 18% of the electricity demand of the department of Córdoba. Additionally, the biogas potential identified is equivalent to 1.4 times the energy demand to support cooking in the 32% of homes using firewood in the department. Moreover, implementing power generation systems based on the direct combustion of biomass wastes is feasible only for the lower capital investment costs available in the market, while for anaerobic digestion it is feasible for the low and average capital investments. More investigation is required in the department to further define the potentialities and promote the implementation of biomass-based renewable energy systems.

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