

Potential of Cogeneration from Sugarcane Bagasse in Mexico as a Decarbonization Alternative

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In Mexico, biomass is the largest renewable source of energy, mainly due to the intensive use of firewood for cooking and heating (67.3%) and the sugarcane bagasse used for cogeneration of thermal energy in sugar mills (32.7%). In the short and medium term, the most promising application for forest biofuels is the combined use of wood chips with residues of sugarcane (bagasse and straw) to cogenerate electricity in sugar mills and ethanol distilleries.

The sugarcane bagasse is usually directly burned in boilers to provide both process heat and electrical power using steam cycles. This paper describes a methodology to determine the amount of biomass available, as well as the potential for generating heat and electrical power when using sugarcane bagasse produced in Mexico as a decarbonization alternative. An estimate is also presented of the tons of CO₂ that would be left to be emitted into the atmosphere due to the use of sugarcane bagasse waste.

The waste generation potential of sugarcane produced in Mexico has been identified and classified as: total potential, accessible potential, available potential, and energy potential. Finally, the potential for generating heat and electrical power when using sugarcane bagasse as a decarbonization alternative is presented.

The estimated potential of electric power generation when using biomass from sugarcane bagasse from the sugar mills of Mexico is de 22.074 MWh, which represents satisfying about 53% of the energy purchased from the Federal Electricity Commission (CFE, for its acronym in Spanish). value translates into economic savings for the sugar mills, contributes to reduce the use of fossil fuels and in addition they would stop emitting approximately 353 tCO₂ / MWh (tons of carbon dioxide per MWh of energy consumed) into the atmosphere.

1. Introduction

The demand for energy in the agroindustrial sector has generated great interest in research, innovation and development of new strategies, methodologies and technologies to produce energy, as well as sustainable fuels, including the recovery of synthesis gas from sugarcane bagasse for cogeneration of energy. Synthesis gas is a by-product of the gasification of sugarcane bagasse. In this paper, an estimation of the generation potential of sugarcane residues produced in Mexico and an evaluation of the energy generation potential is carried out. Finally, an estimation of CO_{2eq} emissions avoided to the atmosphere is carried out to evaluate the feasibility of synthesis gas in energy cogeneration systems as a decarbonization alternative. The prominence of agriculture as a system for the production of biomass products that can be transformed into fuels includes three important aspects in the promotion of biofuels obtained from agricultural residues: first, the opportunity they offer to alleviate the energy problem, due to the urgent need to reduce dependence on coal and oil; second, the environmental benefit due to the need to reduce CO₂ emissions that cause the greenhouse effect and global overheating of the planet; and third, the need for agriculture in some countries to be competitive in a globalized economy.

In recent years the trend is the reduction of CO₂ emissions, however, in the year 2020 the production of electric energy depended 75% on fossil fuels and only 4.7% was obtained through efficient cogeneration (CENACE, for its acronym in Spanish). Cogeneration and local self-supply of energy reduces energy losses and recovers the transmission, transformation and distribution capacity of the electrical system, additionally, generation is released in peak demand hours and the emission of polluting gases is reduced. In Mexico, the cultivation of sugar cane is of great socio-economic importance, according to statistical information from the National Committee for the Sustainable Development of the Sugar Cane (CONADESUCA, for its acronym in Spanish), this activity generates permanent employment for more than 300,000 people, the surface which is intended for cultivation is approximately 620,000 hectares (ha), distributed in 15 entities and 54 sugar mills, which are obtained productions of approximately 48 million tons of cane, and 4.6 million tons of sugar.

The sugar industry has been successful in using residual biomass for energy purposes. Sugar mills often operate by burning sugarcane bagasse for cogeneration. Valdez et al. (2010), point out that the biomass potential in the sugar sector is considerable if one takes into account that, for every 100 tons of cane processed, between 10 and 12 tons of sugar are obtained, and between 25 and 30 tons of bagasse, and 10 to 20 tons of agricultural waste remain in the field, of which between 5 and 7 tons can be collected as straw.

According to CONADESUCA, during the 2017-2018 harvest the country's mills consumed 18 million liters of fuel oil, 80% less than in 2016. This demonstrates the importance of cane bagasse as fuel. In most sugar mills in Mexico, the back pressure boilers used produce steam with relatively low pressure and temperature. On the other hand, with high-pressure boilers and condensing or extraction turbines, electricity could be generated in periods outside the harvest and surplus energy could be exported to the grid.

The advantages of producing electric energy from cane bagasse are the following:

- 1) Decentralized generation, performed near consumption sites;
- 2) The possibility of extra income from the energy generated by selling electrical surpluses;
- 3) Electricity bill reduction;
- 4) Power generation using cane bagasse as a decarbonization alternative.

2. Methodology

The present study focused on the use sugar cane residues in Mexico. The amount of these residues depends mainly on six factors, namely: harvesting system (burnt or unburned cane), topping height, cane variety, age of crop (stage of cut), climate and soil; Dias and Oliveira (2005). J. Smithers (2020), mention that up to 40% of the total sugarcane biomass can be composed of foliage and that approximately one-third of the energy available from sugarcane is contained in the tops and leaves, commonly referred to as trash, which are generally either burnt prior to harvesting or are not recovered from the field. Moreover, indicate that tops and leaves make up from 188 to 350 kg per-ton of total sugarcane mass and 110 to 170 kg of dry matter per-ton of sugarcane, and recommend that 150 kg of dry matter in leaves and tops per-ton can be considered a good assumption of average availability of sugarcane bagasse. On the other hand; Dias and Oliveira, suggests that the potential for sugarcane bagasse (dry mass - DM) is about 18.3%, which means that for every ton of residues, there are 183 kg of dry residues. This is the value considered for estimating the potential of bagasse waste available in Mexico for energy generation.

The cultivation of sugarcane generates a substantial amount of waste. CONADESUCA reports that in the last 5 years in Mexico about 41 million tons (t) of bagasse waste have been generated during the period in which sugarcane fields are harvested for processing at the mills. The residues of this crop consist of the inedible parts of the plant that are left in the fields after the target crop is harvested, such as the leaves and tips of the cane. An amount of these residues is used to generate steam in their processes by burning them directly in their boilers, while another significant amount is left in the fields to decompose in the environment or be burned in the open, which implies high CO₂ emissions to the environment.

Based on information from similar evaluations, the average availability of bagasse crop residues was estimated at 0,3 with a moisture content of 50%, which is the case for bagasse in Mexico.

The potential for generating sugarcane waste produced in Mexico was classified as: total potential, accessible potential, available potential, energy potential and finally the potential for generating electricity.

Total potential: Potential derived from all the sugarcane crop residue that is cultivated in Mexico, which is calculated based on statistical indicators and coefficients.

$$P_t = (G_a) * (C_r) \quad \text{Eq. (1)}$$

Where: P_t= Total potential (t); G_a= Annual generation of sugarcane (t); C_r = Coefficient of residues equal to 0.3,

based on the data reported by different authors, Vimal (1979), Webb (1979) and BEPP (1985) where the moisture content of sugar cane bagasse is of the order of 50%. Bhattacharya et al. (1993).

Annual accessible potential: Part of the total potential that can be managed, collected, transported, stored in a viable way, this potential represents the waste available for energy generation (how much of what is harvested is not used and is available as potential bioenergy), potentially available waste.

$$P_A = (P_t) * (Fd) \quad \text{Eq. (2)}$$

P_A = Accessible potential; Fd = residues availability factor. It is estimated from the total sugarcane crop in Mexico and the bagasse obtained, as reported by CONADESUCA is 29%.

Available Potential: Dry mass residues, obtained by subtracting the moisture contained in the bagasse.

$$RDM = (P_a) - [P_a * \% \text{ humidity}] \quad \text{Eq. (3)}$$

Where: RDM = Residue Dry Mass (t); % humidity = Percentage of humidity contained in sugarcane bagasse.

Potential for electricity generation: Potential for annual electricity production, where the average conversion rate is 17,52 kWh/ton of dry mass, a value reported in the statistical report on the agro-industrial sector of sugarcane bagasse; Easterly and Burnham (2009).

$$MWh = (RDM) * (\text{energy generation per ton of cane}) \quad \text{Eq. (4)}$$

The results obtained in this study refer to the generation of electrical energy. From the energy point of view, the use of sugarcane bagasse residues a reduction in the use of fossil fuels for a given process is achieved. The amount of CO₂ emissions avoided can be determined by equation 6:

$$E_{CO_2} = Es * FE \quad \text{Eq. (5)}$$

Where E_{CO_2} : Emissions (tCO_{2eq}/year) and Es : Energy saved (kWh/year), is the energy that would not be purchased, because that energy would be generated with the sugarcane bagasse. FE : Emission factor (0,113 tCO₂/MWh).

CO_{2eq} emissions per MWh are estimated from the perspective of energy generation with different types of fuel, considering the process of the life cycle stages of sugar cane bagasse, Figure 1, this biomass as fuel has emissions considered neutral, in the sense that the CO₂ emitted in combustion has been previously absorbed from the atmosphere. Therefore, sugarcane bagasse is considered to have an emission factor of zero, according to the National Institute of Ecology and Climate Change (INECC, for its acronym in Spanish).

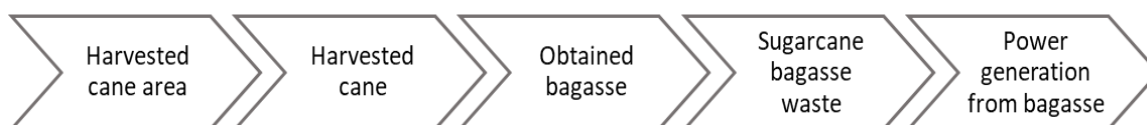


Figure 1: Life cycle stages of the sugarcane bagasse

With the use of sugarcane bagasse residues it is possible to reduce the use of fossil fuels for a certain process, this allows the reduction of CO_{2eq} emissions to the atmosphere and therefore is considered a feasible alternative to achieve decarbonization. Table 1 shows the rate of emissions in tons of CO_{2eq} per MWh for each type of fuel.

Table 1: Index of emissions in tonnes CO_{2eq} per MWh by fuel type (IPCC)

Fuel	Tons of CO _{2eq} per MWh
Coal	0.987
Natural gas	0.644
Oil	0.778
Diésel	0.895
Sugar cane bagasse	0.113

3. Results

Estimating the potential for generating electricity and process heat from sugarcane bagasse in Mexico can be an effective tool for understanding the amount of these wastes and for planning the generation of energy from this biomass.

The values of area of sugarcane harvested, bagasse generated as biomass and electricity consumption of the sugar mills in Mexico are shown in Table 2. Purchased electrical energy refers to the electrical energy that mills must purchase from external sources to satisfy their energy demands.

Table 2: Statistics of the agroindustrial sector of sugarcane in Mexico, harvest 2008-2009 / 2017-2018*

Indicator	Measurement unit	2017-2018	2016-2017	2015-2016	2014-2015	2013-2014
Harvested cane area	Ha	784.661	777.078	778.930	783.515	790.481
Harvested sugar cane	Tonne	51.218.400	51.156.048	52.085.149	51.520.047	52.246.817
Bagasse obtained (biomass generated)	Tonne	15.187.269	15.222.471	15.294.620	15.66.887	15.473.161
Purchased electrical energy	kWh	41.105.154	41.105.154	41.105.154	41.105.154	41.105.154

The calorific value and humidity of biomass are the main parameters for evaluating the potential for cogeneration of energy. The characteristics of the synthesis gas generated with sugarcane bagasse are shown in Table 3. The energy content of this gas, compared to other fuels is different, bituminous coal has 30.2 MJ/kg, wood 19.8 MJ/kg (dry) and sugarcane bagasse has approximately 18 MJ / kg (dry) on average; Sheth and Babu (2009).

Table 3: Synthesis gas characteristics

Sugar cane bagasse	
HHV (MJ/kg)	18.75
LHV (MJ/kg)*	17.44
Composition (%)	
C	36.4
H	4.79
S	0.01
O	37.18
N	0.15
H ₂ O	19.36
Ash	2.11

HHV= Highest Heating (calorific) Value, LHV= Lower Heating (calorific) Value; (*) Suleiman, J., Lima, M., Carvalho, I. (2005).

From the amount of bagasse waste presented in Table 3 chemical composition and calorific value of bagasse shown, the total potential can be determined by equation (1) and was of 14.014.033 Tons, Accessible potential, and Available potential can be determined by equation (2) and (3), resulting in 2.550.554 and 1.259.973 Tons, respectively. The annual available potential of sugarcane bagasse is multiplied by the generation of electrical energy per ton of cane, with this methodology, the annual amount of feasible power generation to cogenerate in sugar mills can be determined. The results of the amount of power cogeneration delivered from the estimated potential of sugarcane bagasse waste in Mexico, as well as the electric power purchased from outsiders to cover their electric power demand are shown in Table 4.

Table 4: Energy cogeneration potential

Annual electricity cogeneration potential (MW) LHV 17,44 (MJ kg ⁻¹)	
Electric power generation	22.074
Purchase of electric power	41.105

The estimated potential for energy generation from sugarcane bagasse residues from Mexican sugar mills is of the order of 22 MWh, which represents about 53% of the energy that is purchased. This value translates into economic savings for the mills and contributes to a reduction in fossil fuel consumption.

Figure 2 shows that the generation of CO_{2eq} emitted by purchased electricity is in the order of 4,645 tCO_{2eq} / MWh, while that generated from sugarcane bagasse is 4,292 tCO_{2eq} / MWh, which means that approximately 353 tCO_{2eq} / MWh would be avoided into the atmosphere.

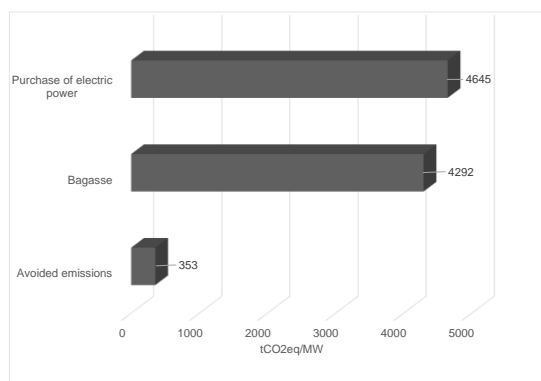


Figure 2: Amount of CO_{2eq} emitted per generation source

4. Discussion

The experience of other countries Otchere-Appiah (2014), shows that it is possible to use biomass in different applications to satisfy many energy needs, which contributes to the country's energy diversification, contributes to economic development and, above all, is a sustainable energy source. As shown in Table 4, the available potential is sufficient to replace about 53% of the energy electrical purchased. This result shows that bagasse waste is a biomass that can be used in Mexico as a primary energy source to satisfy the energy demands of the mills. If emissions to the atmosphere can be reduced (Figure 2), then Mexico will be able to meet its commitments under the Paris Agreement. Because the country has committed to undertake a series of ambitious climate change adaptation and mitigation measures, including the generation of clean energy, the substitution of fuels such as coal and fuel oil in industry, and the control of black carbon, which contributes to the decarbonization of the energy sector. Despite this situation, Mexico could reach a very high biomass potential by 2030, however the values reported depend on the sources and assumptions taken into account.

The CO_{2eq} emissions generated from the generation of energy with sugarcane bagasse are reduced by around 8% compared to the generation of energy from fossil fuels, due to the high sulfur content of the latter, which means that generation from biomass waste contribute to decarbonization.

5. Conclusión

In this paper, a simple analytical methodology was presented to estimate the energy potential of sugarcane bagasse available in Mexico. With this methodology, the total potential, accessible potential and available potential can be estimated, and from these parameters, the potential for electricity generation is determined.

This methodology is sensitive to the variation of the parameters considered in this study, highlighting that the moisture content of sugarcane bagasse determines the energy content of the residual biomass, which is the amount of energy per unit mass of this material to be used as energy. It has also been shown that the moisture content determines the amount of available dry mass that can be considered as potential available for energy generation.

The results shown that the total potential of sugarcane bagasse after the harvest is about of 15 million tons in the Mexican territory, this value was estimated considering an average of the last 5 cultivated harvests in Mexico. The available potential of sugarcane bagasse biomass that can be considered, once the parameters of moisture and energy content have been analyzed, is dry biomass, which was of the order of: 1 million tons.

For biomass to be used and considered intensively, it is necessary to develop a regulatory framework that strengthens the current legal and juridical framework to promote the sustainable use of bioenergy. With these measures it is possible to take advantage of available biomass, thus contributing to Mexico's energy transition and the decarbonization for the mitigation of GHG emissions, and this can be achieved with a significant participation of bioenergy, especially in the electricity, transportation, industrial, residential and agricultural sectors. If sugarcane bagasse waste is used as a raw material for power generation, the CO₂ emitted to the atmosphere can be reduced by about 8%, 53% of the electric power demand of the mills can be satisfied and,

in some cases, can be generated thermal power as process heat, which demonstrates the feasibility and versatility of biomass as a renewable energy source.

References

- A. Koopmans and J. Koppejan. Agricultural and forest residues - generation, utilization and availability. Regional Wood Energy Development Programme in Asia, (1997).
- Aldana, H., Lozano, F.J. y Acevedo, J. (2014). Evaluating the potential for producing energy from agricultural residues in Mexico using MILP optimization. *Biomass and Bioenergy*, 67, 372-389.
- BEPP, (1985), Bangladesh Energy Planning Project: Draft Final Report, Rural Energy and Biomass Supply, Vol. IV.
- Bhattacharya, S.C., Pham, H.L., Shrestha, R.M. y Vu, Q.V. (1993). CO2 emissions due to fossil and traditional fuels, residues and wastes in Asia, AIT Workshop on Global Warming Issues in Asia, 8-10 September 1992, AIT, Bangkok, Thailand.
- CENACE, Centro Nacional de Control de Energía, (2022). Programa de Desarrollo del Sistema Eléctrico Nacional 2021-2035. México.
- Comité Nacional para el Desarrollo Sustentable de la Caña de Azúcar. (2018). Informe Estadístico del Sector Agroindustrial de la Caña de Azúcar, ZAFRAS 2007/08 - 2016/17.
- Easterly, J.L. y Burnham, M. (2009). Overview of biomass and waste fuel resources for power production, *Biomass and Bioenergy*, 10(2-3), 79-92.
- F. Augusto Pazuch, C.E. Camargo Nogueira, S.N. Melegari Souza, V. Cavaler Micuanski, L. Friedrich, A. Miguel Lenz. (2017). Economic evaluation of the replacement of sugar cane bagasse by vinasse, as a source of energy in a power plant in the state of Paraná, Brazil. *Renewable and Sustainable Energy Reviews*, DOI: 10.1016/j.rser.2017.03.047
- G. Otchere-Appiah, E. B. Hagan. (2014). Potential for electricity generation from maize residues in rural Ghana: A case study of Brong Ahafo Region. *International Journal of Renewable Energy Technology Research*, Vol. 3, No. 5, pp. 1 – 10.
- INECC, Instituto Nacional de Ecología y Cambio Climático, (2015). Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero.
- Informe IPCC, (2015). Quinto Informe de Evaluación del Panel Intergubernamental de Naciones Unidas sobre Cambio Climático
- J. Smithers. (2014). Review of sugarcane trash recovery systems for energy cogeneration in South Africa. *Renewable and Sustainable Energy Reviews*, 32, pp.915-925, DOI: 10.1016/j.rser.2014.01.042
- Karina Ribeiro Salomon, Electo Eduardo Silva Lora. (2006). Estimate of the electric energy generating potential for different sources of biogas in Brazil, 1101-1107.
- L.A Dias Paes and M. A de Oliveira, (2005). Potential trash biomass of the sugar cane plant. Programa das Nações Unidas para o Desenvolvimento. Piracicaba, Brazil: Centro de Tecnologia Canavieira; pp.19–23.
- Morales, M. Montiel M. (202). Análisis teórico de la cogeneración de energía en una microturbina de gas a partir de la gasificación de biomasa residual, Tesis de Doctorado. México.
- R. Jiménez Borges, E.J. López Bastida, F. González Pérez, J.A. Curbelo García. (2018). Evaluación preliminar del potencial energético de diferentes biomasas en la provincia de Cienfuegos. *Revista Centro Azúcar*, 45.
- Rios, M. y Kaltschmitt, M. (2013). Bioenergy potential in Mexico - status and perspectives on a high spatial distribution. *Biomass and Bioenergy*, 81, 429-437.
- Rodríguez, D. C., & Fernández, X. S. (2014). La Producción De Energía Eléctrica a Partir de la Biomasa Forestal Primaria: Análisis del Caso Gallego. *Revista Galega*
- Secretaría de Energía. (2019). Balance Nacional de Energía, 58-60.
- Sheth, P., Babu, B. (2009). Experimental studies on producer gas generation from wood waste in a downdraft gasifier. *Bioresour Technol*, 100, 3127-33.
- Sources gas applications, Application Bulletin AB-2-85. El Paso, TX: Cummins Gas Engines, Inc.; (1985).
- Suleiman, J., Lima, M., Carvalho, I. (2005). Biomass power generation, sugar cane bagasse and trash, PNUD.
- Valdez, I., Acevedo, J., y Hernández, S. (2010). Distribution and potential of bioenergy resources from agricultural activities in Mexico. *Renewable and Sustainable Energy Reviews*, 14(7), 2147-2153
- Vimal, O. y Tyagi, P. (1984), Energy from Biomass, An Indian Experience.
- Webb, B. (1979). Technical Aspects of Agricultural and Agroindustrial Residues Utilization, Proceedings of UNEP/ESCAP/FAO. Workshop on Agricultural and Agroindustrial Residue Utilization in Asia and Pacific Region.