

# Possibilities of waste to energy systems based in the co-gasification of municipal solid waste and coal in Colombia

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# Abstract

Getting energy from waste is one of the best alternatives for sustainable handling of waste. Mass burning is generally the preferred option. Usually this applies to large facilities where more than 500 tons of waste per day are treated. Syngas production from waste has also been tried with mixed success. This presentation reviews the situation in this field and proposes an alternative based on co-combustion with coal as a possible route, applied preferably to the treating of municipal solid waste and biosolids from small or medium sized municipalities, producing less than 200 tons of waste per day, with the aim of generating electric energy. For this, a theoretical model is proposed and applied to a specific case for the situation in Colombia.

**Keywords:** Waste to energy, municipal solid waste, design, modeling, syngas composition, technologies, experience, electric energy, coal, co-combustion.

#### 1- Introduction - A review of the MSW problem in Colombia

This paper deals with the possibilities of making use of municipal solid waste in combined gasification systems with coal to help solving two situations. One is the need for a more sustainable use of high available coal resources and the other one is the need for a more sustainable handling of domestic solid wastes, which are not properly disposed. When these two combine, as is the case for a country like Colombia, there are real spaces for the use waste to energy technologies.

Coal is an abundant resource in many places of the world. Unfortunately, the combustion of coal has been clearly associated with the generation of CO2 and global warming, which has caused a tendency to gradually abandon coal as an energy resource, preferring natural gas and renewable energy. This is a worrying situation for a country like Colombia, which possess very large coal deposits. Currently this country is exporting large amounts of coal and this contribute largely to the generation of income. In this sense, it is important to find applications for coal, both in chemical process and more sustainable energy systems and find ways for CO2 recovery and conversion that allow for the continuous use of coal.

The waste problem is very important in developing countries like Colombia. With 46 million people in 2017 and its population mostly concentrated in the Andean highlands and along the Caribbean coast, it has 31 cities of more than 200.000 habitants and 65 with more than 100.000, being one of most urbanized countries in the region, its urban population estimated at 76%. Informality and poverty are big problems, and this comes associated with informal waste recycling practices. With a medium generation of 0.54 kg/hab./day, the estimated daily generation is around 26.000 tons. Colombia is a model in the region in the recycling of paper and cardboard, with a recovery of 57%. This has to do with the existence of industrial plants able to use these materials in their process, which has favored a wellorganized recycling scheme. Currently in the country the recycling rate of waste such as paper, cardboard, glass, metals and plastics is 17%, and by 2019 the goal will be to achieve a recycling target of 20% as result of the implementation of regulatory instruments in the public cleaning services and the tariff frameworks, processes that the national government advances. The rest of the waste goes to waste dumps or sanitary landfills as there are not any thermal treatment facilities in the country. Very few of the landfills facilities have lixiviates treating plants or methane burning systems. Space is becoming an issue and there are growing concerns and limitations about the growth of the landfill system areas in the coming years. In other cases, environmental concerns are becoming more and more important. [1],[2],[34],[35]

# 2. Developing WtE Systems

Waste to energy systems are very important for the sustainable disposition of municipal waste as has been consistently shown in developed countries. This has to do with available technology. In general, in developing countries there is lack of companies that can manufacture equipment for thermal treatment systems capable of handling hundreds or thousand tons per day of mixed waste, burning them in a controlled way, generating

electricity and controlling the air pollution problems related to this. This mean that local responsible waste-handling entities will tend to look for solutions with external providers and this mean usually very high initial investments. As shown in the case of China and India, this can be changed, creating competitive sectors in the WtE technology, able to confront their own situations and to export technology and equipment.

Engineering and design are very important components of the technology necessary to impulse WtE in a country [31,32,33]. Implementing these systems requires detailed studies and planning activities and it is advisable to do the projects considering all the engineering stages. There is always the temptation and the idea that the projects can be accelerated and put into place based on the experience and support of suppliers and makers, by means of EPC developments. The idea being that in such a way the engineering stages can be simplified or even avoided. This normally is a much costlier and rigid solution and does not contribute to developing local technology and desired prosperity. In the solution of the problems, there is ample space to develop a region, as compared to relying only on external provided solutions.

One of the more important stage is the developing of conceptual studies and engineering based as much as possible in local expertise, dully backed, of course with external experience and support. The authors are part of an international working group known as WTERT supported by Earth Institute at Columbia University [3]. The Waste to Energy Research and Technology Council (WTERT) brings together engineers, scientists and managers from universities and industry worldwide and the authors belong to the Colombian chapter, which is supported by ACIEM (Engineering Colombian Association). WTERT tries to identify and advance the best available waste to energy technologies for the recovery of energy or fuels from municipal solid wastes and other industrial, agricultural, and forestry residues. The authors are also project engineers at HATCH, an international engineer company and have experience in waste to energy systems for industrial applications. As part of their work, they participated in a project aimed at using gasification systems based on the co-combustion of coal with biosolids coming from a municipal water treatment system [4]. This paper considers using this technology for waste to energy systems applied to municipal solid waste (MSW). It reviews the situation in this field. This, in order to explore the basis for an alternative based on co-combustion with coal for generating syngas in small or medium sized municipalities, producing less than 200 tons of waste per day. It develops a theoretical model applied to the specific case of municipal waste similar to the one generated at the city of Medellin, where the authors work, co-gasified with available local coal.

Gasification processes involve the reaction of carbonaceous feedstock with an oxygen containing reagent, usually oxygen, air, steam or carbon dioxide, generally at temperatures in excess of 800°C. It involves the partial oxidation of a substance which implies that oxygen is added but the amounts are not sufficient to allow the fuel to be completely oxidized and full combustion to occur [5]. The main product is Syngas which is a mixture of gases including CO and H2, that can be used to produce fuels, chemicals or be burned to generate heat or electricity. Some byproducts are ash and tars depending on the technology used.

#### 3. A review of MSW gasification systems and co-gasification with coal

The basics of the gasification process can be found in many publications and books. MSW gasification have been also an object of many studies and the process details and specificities have been compiled and documented also. Zafar [5] shows the qualitative basics, advantages and disadvantages, as well as classifications depending on the technology, feedstock and reactors, focused on Municipal Solid Waste. Arena [6] presents a deeper treatment of the gasification technology, the chemistry, reactor and technology description and comparison, and environmental aspects. In his thesis, Klein [7] also analyzes these aspects in a deep detail, and also consider investment and operative costs with data of operating plants at that time.

In terms of co-gasification, specific studies have been carried out showing the technical feasibility of the technique, and quantifying the improvements depending on the co-gasification agent. Koukouzas et al [8], analyzed co-gasification of MSW with coal. They evaluated the techno-economic feasibility, of a 30MW(e) co-gasification power plant based on integrated gasification combined cycle (IGCC) technology, using lignite and refuse derived fuel (RDF), in the region of Western Macedonia, Greece. The preliminary cost estimation indicated that this plant is not profitable, due to high specific capital investment and in spite of the lower fuel supply cost and the cost of electricity estimated was not competitive, compared to the prices dominating the Greek electricity market. Hu et al studied, a three-stage system for co-gasification of MSW with high alkali coal char. Tar content was controlled as low as 11.3 mg/Nm3 and HCl to 17.6 mg/Nm3. Lower heating value attains 12.2 MJ/Nm3, meeting the intake-gas conditions for internal combustion engines. They conclude that high-quality syngas can be produced at a steady yield rate of 1.57 Nm3/kg from three-stage gasifier, due to dichlorination and catalytic tar cracking action of high alkali coal char at a low cost [9].

Co-gasification of MSW with switchgrass, using a small commercial-scale downdraft gasifier (100 kg/h) indicate that co-gasification of up to 40% MSW performed satisfactorily. The heating values of syngas were 6.2, 6.5 and 6.7 MJ/Nm3 for co-gasification ratios of 0, 20 and 40%, respectively, in the same cases, the cold and hot gas efficiencies were 60.1, 51.1 and 60.0% and 65.0, 55.2 and 64.4% [10]. Eghtedaei et al, also analyzed co-gasification with biomass and found an improvement in the H2 concentration [11]. The cogasification with the bottom ash has been studied, finding improvements in the final ash quality and the gas emissions without important changes in the operability and syngas quality [12]. These few examples show that in principle, not only the MSW gasification, but also the co-gasification are feasible at different scales, including commercial scale. Many companies or institutes have developed their own process routes with particularities to be more efficient or suitable for the feedstock. In addition to the studies reviewed, some other successful cases could be considered.

Enerkem has effectively developed its own process to obtain methanol and ethanol from MSW through gasification and has an operating plant in Alberta, Canada [13]. Mitsubishi Heavy Industries have a medium size plant in Kushiro Japan, that operates since 2006 processing 240 T/day of MSW (2units x 120T/day), producing 4.6 MW of electricity. Their technology includes ash melting system that improves the ash quality and controls the

dioxin emissions [14]. Currently, Fulcrum-Bioenergy is preparing the construction of a MSW gasification facility in Nevada (USA) to produce 10 million gallons a year of biofuels [15]. Aries Clean Energy have different facilities already working in the USA. In Sanford, Florida, they installed a fluidized bed gasification plant for 30 T/day biosolids from a sewage treatment plant [16]. In Lebanon, Tennessee, a downdraft reactor gasifies 64T/day of biomass to produce heat that is used with Organic Rankine Cycles (ORC) [17]. Same technology was used in Covington, Tennessee with a reactor of 12 T/day mixture of wood residues and sludge moving a 235 kW ORC [18]. In Boral Brick Alabama, 12 modular downdraft systems were used to process residual wood to produce syngas to be burned in brick furnaces. [19]. Tanigaki et al have reviewed the operation of two plants in Japan. They report more than 46 gasification facilities working nowadays in Japan but focused in the two more recent ones, one processes MSW with higher operating hours and lower consumables in Japan. The other one is focused on its waste flexibility, processing not only MSW but also IBA, rejects from recycling center, and sewage sludge. They show the reliability of these plants as well as its effectiveness on the MSW treatment, energy efficiency and accomplish of environmental requirements. [20]

There are many working gasification facilities in the world. A good review of them can be found in the Worldwide Syngas database of the Global Syngas Technology Council [21], here the facilities can be located and filtered by feedstock, product and technology among others. In the following studies, in addition to very good technological reviews of the MSW thermal treatment, especially on gasification, there are sets and lists of plants, facilities around the world with their capacities and owners.

- Thermal municipal solid waste gasification [22]
- Thermal Processing of Waste [23]
- Municipal Solid Waste (MSW) to Liquid Fuels Synthesis, Volume 1: Availability of Feedstock and Technology [24]
- Feasibility Study on Solid Waste to Energy: Technological Aspects [25]
- Gasification of Non-Recycled Plastics from Municipal Solid Waste in the United States: Thermal municipal solid waste gasification [26]
- Thermal Plasma Gasification of Municipal Solid Waste (MSW)[27]

There can be found good examples of feasible and working projects for MSW treatment, however, it is important to note that these projects have specific and contextual difficulties. Hakan Rylander, an experienced actor in WtE, is a bit skeptical with gasification of MSW, mostly because of the heterogeneity of the feedstock, and that the energy balance sometimes has turned out to be negative [28]. Also, GAIA [29], makes an interesting risk analysis of the gasification and pyrolysis of MSW they conclude that "the potential returns on waste gasification are smaller and more uncertain, and the risks much higher, than proponents claim", "Technical and economic challenges for gasification projects include failing to meet projected energy generation, revenue generation, and emission targets. Gasification plants also have historically sought public subsidies to be profitable". At the end of the document, there is a list of ten notable cases of plants and facilities around the world that have stopped operations. There is no general rule to assure se success of a MSW gasification or co-gasification facility, it depends on the technology used, the nature and

variability of the feedstock, and strongly on the local cost and price structure. Where landfilling is still cheap and permitted, WtE tends to be not an economically feasible option. But where waste disposal is becoming more regulated and costly, a WtE plant of this kind is a great option to reduce the amount of material disposed and its inertness while having a benefit that could be directly energy or value-added chemicals.

# 4. Modeling of municipal solid waste and coal co-combustion to generate syngas

This section develops a theoretical model applied to the specific case of municipal waste. The basic information for this is the composition of the MSW and of the coal to be used, plus their heat powers. Tables 1 and 2 show the data used. This tables have been prepared by authors based in several studies made during their work with coal boilers and power plants at Colombia. Two cases are considered for the waste. In the first one, waste as currently generated, it considers the average quality of the MSW in the city of Medellin, which is quite rich in organic materials and so, very high in water content. In the second case, previously separated waste is considered, removing 75 % of organic, 50 % of paper, 20 % of plastics, 55 % of glass, 60 % of cardboard and 50 % of metals of the generated waste. This would amount to a 45 % of the initial as generated MSW.

Water content	% wet basis	7,20
Carbon	% dry basis	68,77
Hydrogen	% dry basis	4,55
Nitrogen	% dry basis	1,27
Oxygen	% dry basis	12,08
Sulfur	% dry basis	0,45
Ashes	% dry basis	12,87
High heat value (dry basis)	KJ/kg	25.911
Lower heat value (wet basis)	KJ/kg	23.155

Table 1. Coal properties considered [30]

Case		As Generated	Separated
Water content	% wet basis	45,58	24,93
Carbon	% dry basis	42,70	38,50
Hydrogen	% dry basis	5,93	5,35
Oxygen	% dry basis	37,95	34,22
Ashes	% dry basis	13,42	21,93
High heat value (dry basis)	KJ/kg	16.244	14.647
Lower heat value (wet basis)	KJ/kg	8.129	10.111

Table 2. MSW properties considered [30]

Gasification is modeled considering three combinations for the co-gasification, identified by the mass ratio of coal to MSW 0, 0.25 and 0.50. Saturated steam was supplied at 4 bar relative pressure (ambient pressure 1 bar) with steam to MSW mass ratios between 0.0 and 1.0 and heated air (120  $^{\circ}$ C) was supplied with air to MSW rates between 1.70 and 5.0. Figure 1 schematizes the basic model used.

The following chemical reactions were considered for the equilibrium calculations in the simulations. No methane generation was considered. Sulfur was controlled by the addition of calcium carbonate at a mass ratio of 0.0163 to coal.



Figure 1. Scheme of the basic model used

An iterative model calculation was developed using the solver routine of MS excel in which the concentrations of syngas were iterated with temperature until the expected convergence was found with species mass balance, energy balance and chemical equilibrium. Iterations were performed as follows:

- Final syngas temperature is assumed
- Volumetric fractions of CO2, CO, H2 and H2O in syngas are assumed
- Fraction of C converted as per reactions 1, 4 and 5 are assumed
- Fraction of O2 converted as per reaction e and forming CO are assumed

- Fraction of CO converted as per reaction 2 is assumed
- With the partial fractions of syngas equilibria constants for reactions 1 to 7 are found.
- With syngas temperatures equilibria constants for reactions 1 to 7 are also found.
- A convergence limit was established for the comparison of these two equilibria constants. This was set as less than 15 % maximum error for each reaction.
- Mass balance was checked for each specie with a convergence limit of less than 5 %
- Energy balance was performed comparing energy formation based on reactions 1 to 7, outgoing syngas enthalpy, incoming vapor and air enthalpy and heat loses (sensible heat, wall and ashes loses). A convergence limit of 5 % was established.

Energy formations (kJ/kmol) used were as follows for syngas forming reactions

-74.520
-241.818
-110.525
-393.509

Enthalpy of syngas was calculated based on syngas composition and specific heat values for each component, depending on temperature, using the expressions of the form:  $Cp/R=A + B \cdot T + C \cdot T2 + D \cdot T-2$ ; T (K) where A to D are constants for each gas component and R is the universal gas constant.

Figures 2 to 8 show the results of the iterations for all major resulting variables. Comments are included for them.



Figure 2. Resulting syngas temperature

Syngas temperatures tend to increase with higher coal to MSW ratios. For each ratio there is a characteristic curve which indicates higher temperatures for lower air to MSW ratios and lower temperatures for higher steam to MSW ratios Temperatures tend to be higher for the case of the separated MSW. Figure 1 indicates the real working ranges for

the simulations. With no coal use the only range of air to MSW ratios that gave convergence in the simulations was in the neighborhood of 1,70. At higher coal to MSW ratios the air to MSW ratio can be higher, all the way to 5,0. Syngas temperatures will be between 600 and 940  $^{\circ}$ C.



Figure 3. Resulting heat value in syngas as % of feed heat value

Syngas heat values tend to increase for higher coal to MSW ratios, but this was not entirely consistent. Syngas heat value simulations showed percentages between 60 and 80 % of feed heat value and this do not change with steam to MSW ratios and tend to decrease with air to MSW ratios.



Figure 4. Syngas flow, kg/kg feed

Syngas flow is linearly related to the studied variables. It increases with air to MSW ratio and with steam to MSW ratios. The values for the simulated range oscillate between 2,5 and 5,0 kg of syngas per kg of feed. The syngas flow is, basically, the result of adding

the incoming flows, discounting the ashes emissions. The behavior and the ranges are quite similar for both situations of MSW studied.

As shown in Figure 5, syngas heat value is quite independent of steam to MSW ratio. It increases with air to MSW ratios and, of course, with coal to MSW ratios. As compared to the MSW lower heat value, it tends to be lower, as expected, for the case of no coal co-gasification. Maximum values tend to be double as compared to MSW heat value, obviously because the impact of coal co-gasification. The values in Figure 5 are consistent to the ones shown in Figure 3. Figure 6 shows the total energy content of the syngas, adding its heat value to the sensible heat associated to syngas temperature. Those two, amount to a value close to the energy value coming from the total feed. It must be said that the incoming hot air and the steam contribute with some energy also, which adds to the outgoing syngas heat value and sensible heat.



Figure 5. Syngas heat value, kg/kg MSW



Figure 6. Syngas heat value and sensible, kg/kg MSW

The behavior of the total energy in the syngas (Figure 6) is quite similar to the behavior of the heat value of Figure 5. The heat value corresponds to the chemical (combustion potential) energy associated to  $H_2$  and CO in the syngas.

Some calculations were carried in the model to determine the potential existing in the syngas to generate electricity. First, the sensible heat potential was determined based on the hot temperature of the syngas. This can be used to generate mechanical work and electricity removing the sensible heat (lowering the temperature, as indicated in Figure 1) in a cycle similar to a Rankine cycle. To determine the potential for this a Carnot cycle efficiency was calculated using as hot temperature the syngas temperature and as cold temperature the ambient value (25°C). With this Carnot efficiency an estimation was obtained of a real efficiency based on existing Rankine cycles in which it is possible to get about a 35 % of the Carnot efficiency. The second estimation was based on expecting an efficiency of 30 % for the cycle used to make use of the combustion heat value of the syngas, considering that it could be taken to an internal combustion engine. Combining these two efficiencies, in proportion to the existing contributions (that of heat value and that of sensible heat in the energy content of the syngas), it was possible to estimate the total efficiency of transformation to electricity and the total potential for electricity generation, which appears in Figure 7.



Figure 7. Potential for electricity generation, kW/kg MSW

This potential is not affected by steam to MSW ratios. It is highly dependent, of course, on coal to MSW ratio and it is higher for lower air to MSW ratios. The potentials are higher for the case of separated MSW (between 0,75 and 2,2 kW per kg of MSW as compared to a range between 0,5 and 2,0 kW per kg of MSW for the as generated MSW case). With these potentials, it is possible to estimate the expected electrical generation for a given flow of MSW. Figure 8 shows the results for a plant processing 200 tons of MSW per day.



Figure 8. Electricity generation, kW, for the processing of 200 ton per day of MSW

These capacities will be between 4.800 kw and 16.000 kW for the as generated MSW and between 6.500 and 17.000 kW for the separated MSW. They are not affected by steam to MSW ratio, increase clearly with coal to MSW ratio and decrease with air to MSW ratio. The ranges indicated in the graphs correspond to the ones for which convergence was found in the iterations, as already mentioned. These plants could generate amounts of electricity quite useful for a given small city in a country like Colombia. Considering a generation of solid waste (as generated) of 0,50 kg/day per habitant, the plant would produce the amounts indicated in table 3 for the cases considered. The table compares these figures to the electric consumption of a country like Colombia, estimated at 3,90 kWh per day per capita.

Parameter	units	As generated	Separated
MSW in Colombia	kg/person day	0,50	0,24
Electricity generated - low	kWh/kg MSW	0,55	0,70
Electricity generated - high	kWh/kg MSW	1,80	2,00
Electricity generated - low	kWh/kg person-day	0,28	0,17
Electricity generated - high	kWh/kg person-day	0,90	0,49
Average Electricity consumption in Colombia	kWh/kg person-day	3,90	
Electricity generated - low	% of national use	7,05	4,38
Electricity generated - high	% of national use	23,08	12,51

 Table 3. Per capita electricity generation potential with syngas plants for the considered cases in Colombia

## 5. Conclusions

The theoretical model showed quite consistent results. It was possible to develop a way of estimating syngas characteristics for the gasification of MSW in co-gasification, within practical working ranges for the studied variables. This, under two extreme conditions for the MSW: as generated in a town with high organic material content and after separation of 55 % of the initial waste for recycling and organics treatment (for example by biological composting and digestion). The model allowed to find the working ranges for steam to MSW ratios (between 0 to 1,0); air to MSW (between 1,7 and 5), for co-gasification with coal and coal to MSW ratios in the range of 0,0 to 0,5

The gasification can generate electricity in all these ranges, with potentials that go from 0,5 to 2,2 kWh per kg of MSW. For the case of a plant processing 200 ton of MSW per day, the generation capacities would be between 4.800 and 17.000 kW. These capacities are entirely within the electricity needs of a country like Colombia. They are between 0,28 and 0,90 kWh per person per day, for the current per capita MSW generated in the country. These figures are to be compared to the current daily electricity per capita use, which is 3,90

From the practical point of view, it is important to use this as a conceptual basis for future work seeking indications on systems that could be feasible. This will help doing the correct steps. Engineering and design are very important components of the technology necessary to impulse WtE in a country. These systems require detailed studies and planning activities and it is advisable to do the projects considering all the engineering stages. There is always the temptation and the idea that the projects can be accelerated and put into place based on the experience and support of suppliers and makers. This by means of EPC developments, in such a way that engineering stages can be simplified or even avoided. This normally is a much costlier and rigid solution and does not contribute to developing local technology and prosperity. In the solution of the problems, there is ample space to develop a region, as compared to relying only on external provided solutions. MSW co-gasification with coal seem to be a possible alternative.

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