RECOVERING ENERGY FROM WASTE

PART A:
MSW Management in the City of Buenos Aires, Argentina and Potential for a Waste-To-Energy Plant

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PART B:
Upgrading Low BTU Fuels to Reduce Emissions in Internal Combustion Engines

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PART A:

MSW Management in the City of Buenos Aires, Argentina and Potential for a Waste-To-Energy Plant

Executive Summary

Solid Waste Management (SWM) is a major concern for most Argentinean municipalities. The population of most Argentinean municipalities is constantly increasing. As a result of the increase, the cities' borders constantly expand and this results to ever increasing land prices in areas closer to the city. These factors coupled with a population who refuse to have waste management facilities located near their houses (phenomenon known as "not in my backyard"), results in landfills located further and further away from population centers. The City of Buenos Aires (CBA or the City) and its metropolitan area were selected as the subject of the present analysis on SWM for its critical role in Argentinean MSW disposal. This area generates 40% of the total MSW of the country. The Accesso Norte III landfill is utilized to dispose of 90% of this waste i.e. 36% of the country's MSW is expected to reach its full capacity in 2012.

In evaluating the current issues arising from the dearth of capacity, WTE is proposed as a solution to the crisis, one that would also be a significant factor in fostering a more sustainable city. This proposal is made despite the existence of Law No. 1854, the so-called Zero Waste Law, which forbids the incineration with or without energy recovery of any of the MSW generated in the City of Buenos Aires (CBA), even if the incineration plant is out of the City's boundaries. The proposed WTE facility would be located next to the Acceso Norte III landfill, where a connection to the grid is available, and would provide several benefits to the SWM system: Much less space to operate compared to a landfill, same distance to the city which avoids increased transportation costs, and the promotion of recycling. The WTE facility would also bring additional benefits such as the delivery of renewable energy to the grid and a decline of greenhouse gas emissions.

Existing cases of WTE implementation around the world have shown that WTE also acts as a recycling promoter, which is another issue that CBA faces. The current recycling system is weak. It consists of two circuits: the formal and the informal. Together these systems recycle only about 6% of the city's MSW. It is estimated that less than 20% of the population separates their residues (cardboard and paper) at the generation point. As part of this thesis, a survey of an educated sample of CBA residents was conducted which reflected that the population is largely unmotivated to recycle due to the belief that either their efforts will not be fruitful or because they lack an understanding of how to separate the residues.

This thesis analyzes the current SWM system and utilizing the results obtained from the survey and proposes a comprehensive overhaul of the SWM system that includes an educational campaign and implementation of WTE in order to increase materials and energy recovery and achieve a more sustainable city.

Contents

1. Introduction

Over the last 10 years, Argentina's population has increased considerably and so has the amount of Municipal Solid Waste (MSW) produced. Despite the efforts of the Government of the City of Buenos Aires (CBA or the City) to meet the regulatory goals of reducing MSW and increasing recycling, the volume of MSW for final disposal has also increased. Consequently, CBA is experiencing a dearth of space for discarding waste. Innovative solutions are continuously being sought and a new Integrated Waste Management Plan is the key to solve the issues the City is facing.

To date, the City's population has failed to develop self-consciousness about environmental issues. As a result, no significant separation of recyclables is occurring at the point of waste origination. However, since 2001 when the biggest economic crisis of the century hit Argentina, informal recycling of paper and cardboard began in the City. Also, as a result of the Government's dissatisfaction with the existing SWM system, CBA started to explore different alternatives. One of these intends to formalize the informal recycling by dividing MSW collection into two streams: A wet stream and a dry stream. However, since a study from the University of Buenos Aires estimated that only 15%[21] of the City's waste, after the informal recycling, is recyclable, it is evident that the City's only alternative for disposal of most of its MSW, after all possible recycling is done, are landfills. However, the land availability for landfills near the City is very limited; the Acceso Norte III landfill that receives 90% of the CBA MSW will reach its maximum capacity by the end of 2012. Given this scenario, this thesis proposes the only proven alternative to landfilling: Waste-to-energy facilities that not only save space – the ash produced after the MSW combustion represents about 10% the volume of the MSW burned[1] – but promotes recycling and also provides a renewable source of energy for the country.

The present work gives an overview of the present situation of MSW in Argentina and more particularly in Buenos Aires, discussing its collection system and disposal, its characterization, and the legal framework around waste management. It also identifies and discusses the main problems that the SWM system of the city is facing and proposes alternative scenarios. Finally, the current situation regarding alternative energies is presented along with some insights (such as pricing) regarding energy supply in Argentina.

2. Solid Waste Management

2.1 Definition and components

Solid waste can be classified by its origin – residential, industrial, institutional, commercial, etc. - , its properties – papers, plastics, organics, metal, glass, ash, inert goods, powders - , or the hazard it poses for human health and the environment – toxic, reactive, corrosive, radioactive, flammable, pathogenic, etc.

'Solid Waste Management' (SWM) involves the entire process starting with the generation of the waste to collection transport, recycling or composting part of it and ending in its final disposal. It includes collection, street sweeping, special services, transfer stations, inspections and treatment and also entails the characteristics of the materials to be disposed (organic, not organic, soft, hard, heat capacity, etc), the economic and the environmental cost of each action, and the lasting effect that it will have on the quality of the environment and its resources. [2]

The proper disposal of MSW is a key part of a SWM System and the methods include recycling, composting, Waste-To-Energy (WTE), and landfilling. The order of preference of these methods is illustrated graphically by the pyramid of the Hierarchy of Waste Management shown in Figure 1.

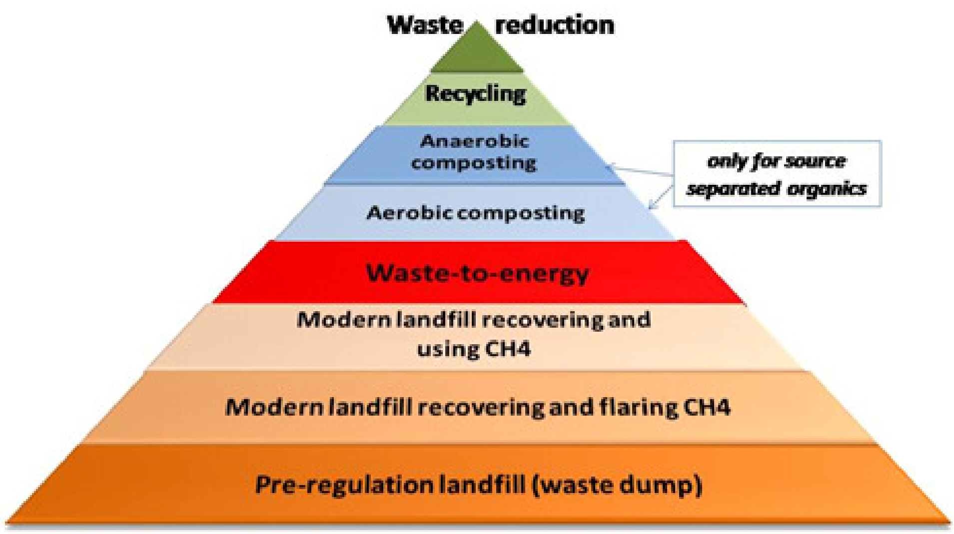

Figure 1 - Hierarchy of Waste Management[3]

The top segment of the pyramid indicates the most desirable option, whereas the bottom indicates the least desirable. However, this hierarchy cannot be applied in all cases because of economics and other considerations. A description of each stage is presented below.

Waste Reduction: This is the most desirable case, with 'zero waste' production. However, it is an ideal condition and cannot be reached in practice. Even in Japan, which will be presented in greater detail later on, where the government and its populace have taken all measures in order to approach the zero waste goal, the waste production is still 0.3533 metric tons per capita per year.

Recycling: Following waste reduction, the hierarchy of waste management leads to recycling. It reduces the volume of waste for final disposal and offers a number of environmental benefits such as the reduction of greenhouse gases emissions, energy consumption, and preservation of natural resources by reducing the amount of raw materials used. However, not every material in MSW is recyclable, and even recyclable materials have a fraction that cannot be recycled practically.

Composting: Both aerobic and anaerobic composting are applicable for organic waste separated at the origin. Normally used to enrich soil quality, as a side effect, it also cuts down the landfill tipping fee by diverting the organics[4]. Many times it cannot be used as such, and is therefore landfilled. Conversely, many times the compost does not meet the requirements to be added to the soil, having to be landfilled.

Waste-To-Energy: The best SWM operation to dispose of the remaining waste, after recycling and composting, is the combustion of the waste with energy recovery or waste-to-energy (WTE). WTE plants burn MSW under controlled conditions and generate steam that is used in a turbine to generate electricity. Typically, a WTE facility generates between 500 to 700 kWh per ton of MSW combusted.[5]

WTE reduces the volume of the waste by approximately 90%[1], leaving the remaining 10% as ash. This ash can be reused in construction applications. In the U.S., less than 5% of this ash is used beneficially because of the lack of national standards regarding the beneficial use of the ash. On the other hand, European countries, or even islands such as Bermuda reuse over 70% of the ash in construction applications.[2]

When the WTE plant burns the MSW as received, the process is classified as 'mass-burn'. When the MSW is shredded and there is some separation of non-combustible materials, the process is known as 'refuse-derived fuel (RDF)'.[6] Figure 2 shows a typical mass-burn WTE facility.

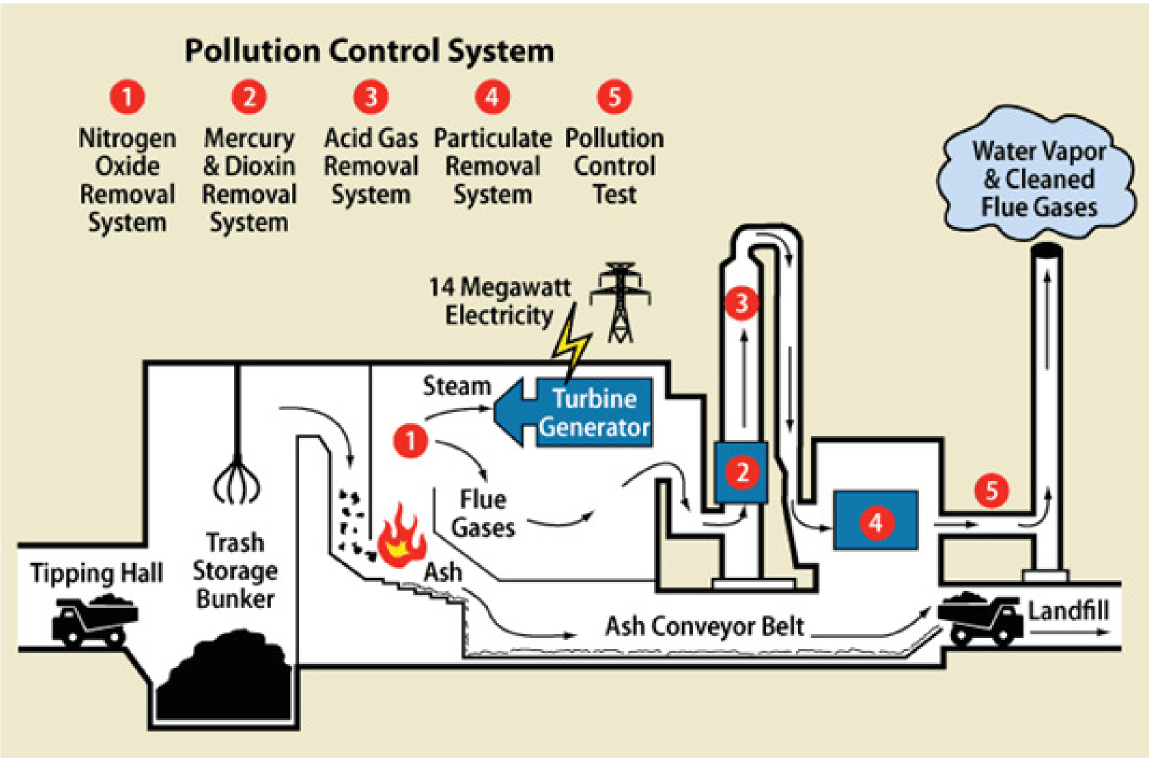

Figure 2 - Typical mass-burn WTE Plant[7]

As shown in the diagram, MSW arrives in trucks and is stored in a bunker. MSW is fed by a "claw" crane to the feed hopper of the combustion chamber, where it is combusted with air, at high temperatures. In this chamber, the refuse usually moves through a grate which has an input air stream underneath that serves not only as a source of oxygen for the combustion, but also cools the grates, reducing the NOx formation. The operating temperature of these facilities can reach up to 2000°F[8] for good combustion and odor elimination, while avoiding the exposure of the refractory materials to excessively high temperatures. The gas output after the combustion is composed of the steam that is derived to the turbine, and flue gases. This stream is usually the carrier of most of the air pollutants, and therefore goes through steps two, three, four and five in order to be cleaned.

Landfilling: Landfills are the most common practice worldwide for MSW final disposal. The U.S Environmental Protection Agency defines landfill as a "waste disposal site in which waste is generally spread in thin layers, compacted, and covered with a fresh layer of soil each day"9. A more complex definition is a waste disposal method that does not generate health or public safety risks or hazards, utilizing engineering principles to confine the waste in the least possible surface area, reduced to the minimum possible volume, and covered by a layer of soil at the end of the operational day, or the most needed frequency.

There is a wide range of landfills, from the most precarious and non-regulated "open dumps" to the most advanced sanitary landfills employing landfill gas capture and utilization as an energy source, including those landfills with landfill gas capture followed by flaring.

2.2 SWM around the world

WTE facilities play a relevant role when referring to modern SWM systems worldwide. With over 700 facilities located in 37 nations[10], WTE is the most advanced waste disposal system currently being implemented. The following section discusses the application of WTE in two highly advanced nations, Austria and Japan.

The Vienna (Austria) Case

With 415km^2, 1,651,437 habitants and a purchase power of €44,241 per capita, Vienna produces 793,599 t/yr of waste, with a recyclable quota of 26%.[11]

Consistently in accordance with the Hierarchy of SWM presented in Figure 1, the City of Vienna has adopted a successful plan of waste minimization since 1990, when a Waste Minimization Pilot Plan was first adopted, achieving a waste reduction/prevention of 15.1%.

During the period from 2004 to 2006, Vienna launched a strong educational campaign on immaterial consumption and strategies on reuse – such as on-line flea markets, repair networks that explain how to repair washing machines, etc.

Following the hierarchy of SWM, Vienna has a Secondary Waste Minimization strategy that consists on recovery. More specifically, and in priority of order:

- Recycling – with and without recovery of slag
- Recovery of organic materials
- Energy recovery – WTE

The implementation of collection containers was the approach adopted to promote recycling, and the non-recyclables were delivered to WTE facilities.[12] As a result of these initiatives, the amount of MSW to landfills decreased by 3.9% and the energy recovered from waste increased by 4.4% in 2005 compared to 1999 levels.[11]

The Japan Case

Near the end of the 20th century, Japan found itself facing several environmental and waste management problems in order to create a Sustainable Society. Among these problems was energy and resource conservation, and waste management including the application of 'the three Rs': Reduce, Reuse, Recycle. In order to achieve the Sustainable Society, Japan had to combat the issues relating to the constraints on the environment and resources as its biggest problems; such as a short remaining life for its landfills– until 2012 for MSW and 2004 for industrial waste.

Consequently, to achieve sustainable development Japan had to change its economic system urgently: from a system of mass production, mass consumption, and mass waste to a recycling oriented society. As a result, in January 2001 a basic law for promoting the creation of a recycling-oriented society was ratified. Thereafter, a number of enforcements followed this law implementing the recycling specifically of home appliances, food, and other materials.

However, the biggest issue was Containers and Packaging (C&P). With a plastic production of 14 million tons per year, Japan was the 3rd largest producer worldwide in 2001. In the same year, the country had a plastic consumption of approximately 85 kg per capita. Japan's C&P Recycling Law was enacted in 1995, partially went into effect in 1997 for glass and PET bottles, and was fully enforced in April 2000 including for plastics other than PET and paper C&P. Even though by 2002 the recycling volume of PET became nine times the volume in 1997 with a recycling rate of 46%, the production of PET bottles also increased to double the 1997 amount. Accordingly, constraints on final disposal remained a problem.

Under this scenario, incineration with energy recovery turned out to be an effective method to decrease the volume of landfilling, accepting only non-recyclable waste. The output of waste power generation was about 1,100 MW in 2001, targeting 12.22 TWh/yr in 2010. In 2003, there were 210 WTE plants on the average processing 300 tons per day each with up to 20% power generation efficiency, four plants processing 400 tons per day with an efficiency between 20 and 35%, and 72 gasification-smelting furnace plants under planning and construction.[13 14]

3. Municipal Solid Waste Management in Argentina

3.1 Argentina overview

Argentina is the fourth largest country in America (2.8 million km2; after Canada, the US, and Brazil) and the seventh worldwide.[15] It has a wide diversity of natural resources and geomorphologic characteristics that has caused an uneven distribution of the population along the country (Figure 4).

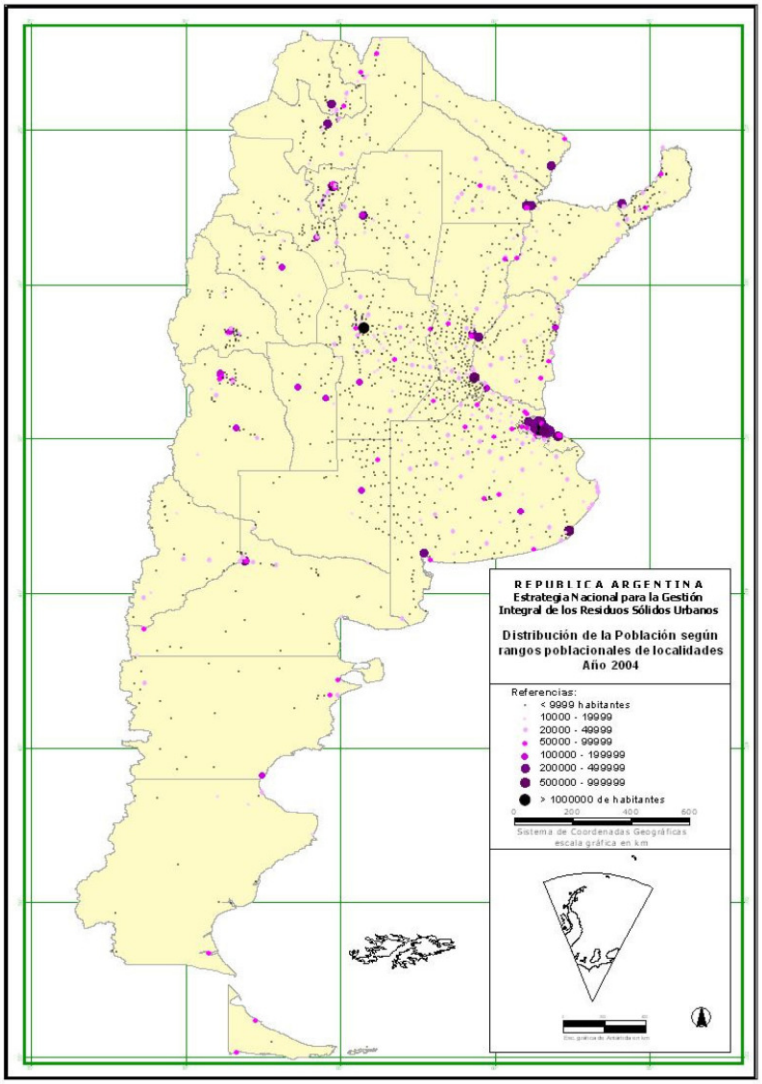

Figure 3 - Population density along Argentina[17]

The Argentine Republic consists of 24 jurisdictions – 23 provinces and the Autonomous City of Buenos Aires, the capital of the nation. The National legislation is applicable to the entirety of the territory but each Province has its own particular regulations.

According to the 2010 census, Argentina has a population of over 40 million people and has increased 10.6% over the population registered by the 2001 census.[16]

3.1.1 Waste management in Argentina

Solid waste management ("SWM") is a major concern for most Argentinean municipalities because it comprises street cleaning, household and public space collection, and the final disposition of municipal solid waste ("MSW"), which in many cases consists of open dumps with very few environmental and technical controls, thereby representing a risk to the public health and to the environment. Moreover, the citizenry typically tends to disentail from what happens to their MSW once they deposit it onto the streets. This is in part because the costs associated with SWM are not shown in the tax contributions and therefore the populace is not aware of these costs.

Because of the division of responsibility between municipalities and Province, and the major differences in SWM systems from municipality to municipality, Argentina established in 2005 the National Strategy for an Integral Urban Solid Waste Management (*Estrategia Nacional de Gestion Integral de Residuos Solidos Urbanos – ENGIRSU*). The objective is to implement a systematic, homogenous, and customizable management model that has a proven efficiency rate and can assure human health and environmental protection and preservation.

There are few studies on the SWM in Argentina at the national level and there are no detailed statistics available regarding quantification, characterization, and other aspects of the SWM. The data presented in this thesis is based on a study from the Secretary of Environment and Sustainable Development of Argentina finalized in September 2005.

Table 1 shows that in 2004, 12.3 million metric tons of MSW were generated in the entire country, with generation rates among the provinces ranging from 0.16 tons per capita in Misiones, to 0.55 in the City of Buenos Aires.

Province	Population (extrapolated to 2004)	Metric tons of MSW per capita	RSU Total (kT/yr)
Buenos Aires	14,312,138	0.30	4,268
Catamarca	359,963	0.25	90
Ciudad de Buenos Aires	2,721,750	0.55	1,493
Cordoba	3,177,382	0.38	1,204
Corrientes	979,223	0.32	306
Chaco	1,053,335	0.22	232
Chubut	433,739	0.35	148
Entre Rios	1,209,218	0.22	261
Formosa	518,000	0.24	122
Jujuy	650,123	0.26	166
La Pampa	314,131	0.36	111
La Rioja	315,744	0.28	88
Mendoza	1,637,756	0.42	678
Misiones	1,033,676	0.16	163
Neuquen	508,309	0.34	169
Rio Negro	571,013	0.32	178
Salta	1,157,551	0.28	316
San Juan	655,152	0.35	226
San Luis	399,425	0.41	161
Santa Cruz	211,336	0.30	63
Santa Fe	3,079,223	0.41	1,235
Santiago del Estero	852,096	0.30	255
Tierra del Fuego	113,363	0.23	26

Tucuman	1,405,521	0.27	369
TOTAL	*37,669,167*	*0.33215*	*12,328*

Table 1- MSW Generated in the Provinces of Argentina (2004)[17]

With respect to waste characterization, it has been estimated that the Argentina MSW contains, on average, over 50% humidity content, about the same percentage of organic materials –on a dry basis-, and 15 to 25% of paper and cardboard.[17]

There are industrial plants in the country, particularly in the metropolitan areas, devoted to processing materials from the waste and industrially recycling or reusing them, particularly plastics, glass, textiles, metals, papers, cardboard, and others. However, these streams of waste are usually delivered to the plants by intermediaries who, in turn, buy them from scavengers that collect them from the streets - commonly known as '*cartoneros*'- or from the open dumps – commonly known as '*cirujas*'. Only in some localities do the inhabitants separate residues on site and utilize a differential collection system, which dramatically increases the efficiency of the recycling aspect.

With regard to composting, it is formally practiced primarily in small cities, although the main areas of the country – Gran Buenos Aires, Gran Córdoba, Gran Rosario –also have composting plants.

As previously mentioned, the final disposal systems vary from open dumps to more advanced landfill structures. Most of the existing landfills have passive vents to avoid pressurization and consequent fissures of the landfill surface and lixiviate leaks. On the other hand, the passive vents release greenhouse gases to the atmosphere faster. Therefore, a few years ago, some landfills incorporated active venting with subsequent gas combustion, which allows them to apply for carbon credits as per the provisions of the Kyoto Protocol. The carbon credits can then be commercialized internationally, generating an economic profit that represents additional financing to manage the MSW.

A more advanced option for landfill projects that would also create carbon credits is energy recovery from collected landfill gas (LFG). LFG is considered a low BTU fuel because it contains roughly 50% of CH4 (the exact composition varies from landfill to landfill), and is therefore a 'free fuel'. Nevertheless, because of its relatively low efficiency, it is usually not easy to achieve an acceptable economic-financial equation with these projects. Despite this fact, some pilot plants have been built such as the one in Santiago del Valle de Catamarca, where the LFG is used to produce steam to sterilize hospital waste in autoclaves, or the larger electricity plant that is currently under construction in the landfill Acceso Norte III that serves Gran Buenos Aires. The generation of electricity from LFG will be further discussed in Part B of the present thesis, where experimental results on enhancement of low BTU fuels research are presented.

Table 2 presents a complete list of the projects registered on the Methane to Markets program (now transitioning to Global Methane Initiative (GMI)) in the Argentinean territory. GMI was launched in October 2010, when thirty-eight governments, the European Commission, the Asian Development Bank, and the Inter-American Development Bank agreed to urge stronger international action to fight climate change while developing clean energy and stronger economies. GMI builds on the existing structure and success of the Methane to Markets Partnership to reduce emissions of methane, while enhancing and expanding these efforts and encouraging new resource commitments from the country partners.

City	Name	Project Type	Stage	Year Start
Buenos Aires	Complejo Ambiental Norte III (IIIB)	Open Flare	Operational	2007
Buenos Aires	Escobar Landfill	Direct Thermal	Operational	2010
La Matanza	González Catán	Enclosed Flare	Operational	2006
La Plata	Complejo Ambiental Ensenada	Enclosed Flare	Operational	2006
Municipality of Gral. San Martin	Norte III Landfill	Electricity Generating	Operational	2005
Olavarría	Olavarría Landfill	Enclosed Flare	Planned	2006
Posadas	Fachinal Sanitary Landfill	Enclosed Flare	Planned	2007
Rosario	Puente Gallego Landfill	Enclosed Flare	Operational	2006
Salta	San Javier I Landfill	Enclosed Flare	Planned	2009
Salta	San Javier II Landfill	Enclosed Flare	Planned	2009
Salta	San Javier III Landfill	Enclosed Flare	Planned	2009
Villa Dominico	district of Avellaneda	Villa Dominico Landfill	Enclosed Flare	Operational

Table 2 - Argentinean Landfill Projects registered on Methane to Markets[18]

At the other end of the landfill spectrum are the open dumps. In most cases these dumps are located in undesirable or depreciated lands, or territories susceptible to floods that are close to water bodies that often drag waste downstream. In addition, there are issues related to the saturation and end of life of the open dumps, issues that cannot be solved by increasing taxes because of the low economic level of the population in most of these areas, or because of poor municipal administration. As a result, short term solutions are always applied to these issues, never getting to the root problem.

3.2 Current SWM difficulties

The rapid demographic increase, the socio-economic development of the population and changes in the commercialization strategies of massive consumption products have occurred faster than the necessary changes in the government agencies who have to deal with their effects.

The Secretary of Environment and Sustainable Development of Argentina identified through its National Strategy for the Integral Management of the Urban Solid Waste (*ENGIRSU*) in 2005[19] the main issues in the current SWM situation as follows.

Legal aspects: There are gaps in the current regulations related to solid waste and its adequate management.

Institutional aspects: There is a need to strengthen the design, planning, implementation and management know-how related to the integral SWM system, at a technical and administrative public and municipal level.

Technical and Operative aspects: Reliable statistics on waste generation rates, composition i.e. commercial v. residential, management systems, and other key information are lacking, in addition to methodic criteria and techniques to carry on studies associated with the design, optimization, planning, administration, operation, maintenance and closing of the various technical operative components of the SWM. There is also deficiency of policies to promote minimization, reuse, and recycling of MSW. Moreover, there are many faults connected to MSW's final disposal in many Municipalities along the country, along with poor development of the recycling material businesses.

Health and Environmental aspects: In addition to the presence of many open dumps –the quantity of which are not even estimated – that represent a threat for human health and the environment, most particularly to the human settlements around them, Argentina lacks a data center of epidemiologic data specific to sicknesses related to MSW. The omission of any significant coordination between the municipal plans on land and environment to handle the MSW, including its final disposal, transportation, transfer, regionalization, and other issues also constitutes a problem.

The very wide spread informal collection, somehow out of control, carried by a diverse population of which a significant portion is children or scholar aged young people. Despite the Government's efforts, the vast majority of this group has no sanitary protection or health care.

Financial aspects: The Municipalities are lacking analytical mechanisms and costs, economic controls, expenses, and rates application definitions, and there is also a need to revise and adjudicate the taxation norms applicable to the MSW. The population is unaware of the costs and benefits of the current SWM system (this argument is also backed up by the survey attached as Exhibit A, which evidences the deep level of unawareness of the population with regard to MSW and SWM) and there are evident flaws in the Argentinean MSW market as externalized costs, imperfect information mechanisms, and general under development of the recycling market concerns. Additionally, there is no knowledge on the indirect costs (particularly health care) due to deterioration of the population's quality of life. Finally, there are no self-financing sectorial mechanisms at a Municipal level, and a low collection percentage of the rates due to impossibilities from the population to pay and an evident need of additional financial and economic resources to make all the required modifications happen.

Social Aspects: Strong social opposition to initiatives to construct infrastructure or installations to the SWM system paired with a lack of official diffusion and restricted access to information resulting in covers the ignorance of the populace on the issues presented by MSW leads to little participation from the community on SWM matters, particularly on consumption matters, reuse, and recycling. Further there are no incentive system in place to encourage the population to take action on the issue. Lastly, little contribution is made by the municipalities on the local decisions regarding service provision.

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In addition to the expressed issues, it is important to consider that Argentina has a 90% urbanization rate and therefore its SWM system results are particularly critical in the cities. Table 3 shows the constantly increasing urban population during the years 1991-2003.

Year	Total Urban Population
1991	28,354
1992	28,838
1993	29,329
1994	29,821
1995	30,309
1996	30,794
1997	31,279
1998	31,763
1999	32,247
2000	32,729
2001	33,258
2002	34,024
2003	34,393

Table 3 - Evolution of the urban population in Argentina from 1991 to 2003[20]

The phenomenon 'not in my backyard', regarding SWM, refers to a generalized –and expected - attitude from the population who are conscious that the waste has to be disposed of but nevertheless, refuse to have waste management facilities located near their houses. This observable fact, added to the constantly growing population of the cities that expands the cities' borders over time and constantly increases land prices in areas closer to the city, results in landfills located further and further away from population centers. Since Buenos Aires and the Metropolitan Area together constitute 40% of the total MSW of the country, this location was selected to perform the present analysis on SWM.

4. Municipal Solid Waste Management in Buenos Aires

4.1 Buenos Aires overview

Despite being known as 'the City of the 100 neighborhoods', Buenos Aires is formed by 48 neighborhoods whose lands total 200 km2 of territory. Each neighborhood has its own characteristics, and the income of its population can vary significantly.

'Gran Buenos Aires' is the name given to the City of Buenos Aires plus the Metropolitan area, the natural extension of the province of Buenos Aires that is formed by the 24 adjacent parties. This region covers 2,750 km2. The Metropolitan area is considerably relevant to the dynamics of the city as will be explained in the next paragraphs.

This City of Buenos Aires has a population of 2.9 million and the Metropolitan Area another 9.9 million so that the Gran Buenos Aires constitutes about 32% of the population of Argentina. This study concentrates on the waste management system of this important part of the nation. The area generates 4,730tn/d of MSW[21] which divided by its population gives a MSW production of 0.597 metric tons per capita. Note that this daily production rate also includes the MSW generation of 1.6 million people[21] who commute to the Capital.

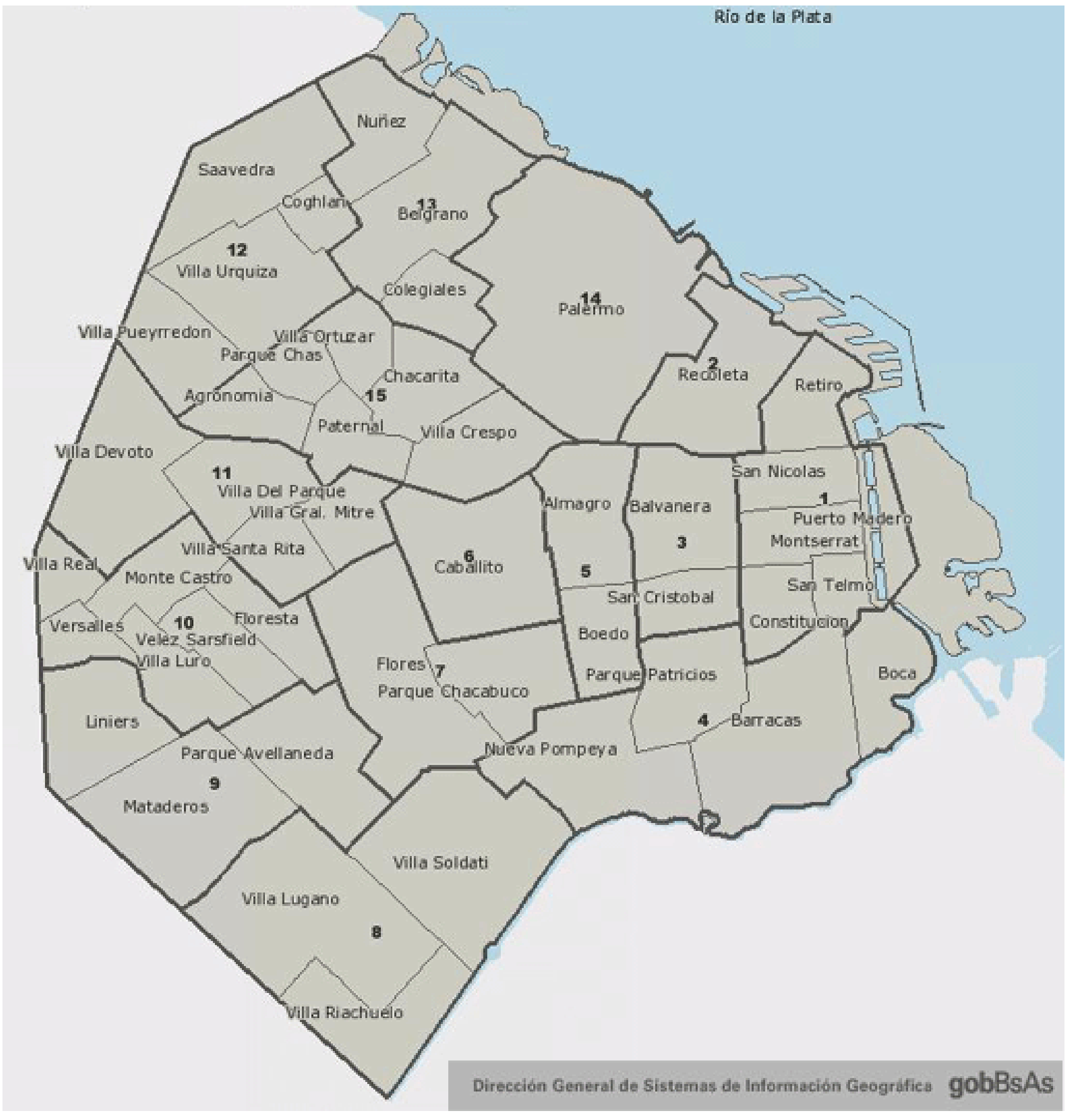

Figure 4 - Map of the City of Buenos Aires and its 48 neighborhoods[22]

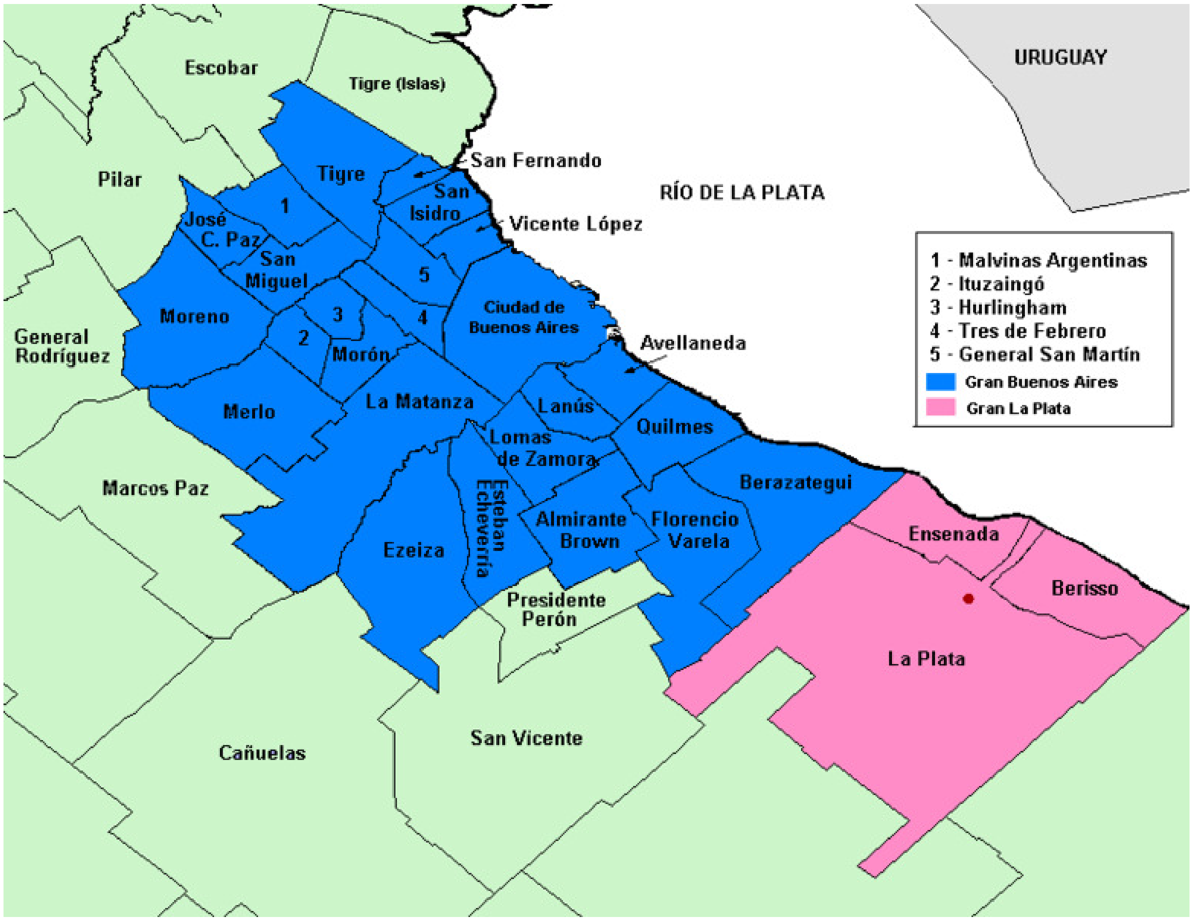

Figure 5 - Map of the City of Buenos Aires and its 24 adjacent parties: 'Gran Buenos Aires'[23]

Table 4 shows the evolution of population size in the City of Buenos Aires and the Metropolitan Area, with the growth rate between the different time periods.

Jurisdiction	Population 1991	% of the total population	Population 2001	% of the total population	Population 2010	% of the total population (2010)	Variation 91/01	Variation 01/10
City of Buenos Aires	2,965,403	9%	2,776,138	8%	2,891,082	7%	-6%	4%
Metropolitan Area	7,950,427	24%	8,684,437	24%	9,910,282	25%	9%	14%
Total of the Country	32,615,528	100%	36,260,130	100%	40,091,359	100%	11%	11%

Table 4 - Total population of the City, the suburbs and the Country in 1991, 2001 and 2010[24]

The variation of the population between 2001 and 2010 gives an average growth rate of 0.44% per year in the City, and 1.2% in the Country.

4.2 SWM History

SWM in Argentina was a concern since CBA was founded by Juan de Garay. In that era, the Cabildo – seat of the political committee during colonial times- was the Institution responsible for the hygiene of the city and it was their common practice to throw SWM in open dumps in the country. In 1822 the Police took over all of the responsibilities that the Cabildo used to handle, including sanitation. The Municipality was established in 1856 at which time the Police were suppressed and replaced by the figure of the 'Mayor of the neighborhood' whose only function was to be in charge of the City's hygiene to prevent population from epidemics. Along with the Mayor of the neighborhood, a Public Hygiene Board was created. Even though there was improvement on the collection system throughout these years, the MSW disposal and treatment system was still conducted in the same way.

Due to the increase in the production rate of MSW during the 1860s an interest for a more efficient way to dispose of the MSW was developing in the city, starting with incineration practices until 1873, when open sky incineration was formally implemented. There was a big site that received all of the MSW from the city. The Municipality signed contracts with 'business men' who were in charge of performing the combustion, after separating the reusable goods: furniture, bottles, metals, glass, bones, cloths, paper, and others. Until the end of the Century, there were different contractors. However, the method lost effectiveness when there was less MSW disposed of because a group of people started collecting the commercial portion of the waste: the initiation of the 'scavengers'. In addition, the land where the MSW was taken was closed in 1888 because of odors and complaints of discomfort from the neighbors.

By the end of the XIX Century the impacts and hazards produced from the open sky incineration turned into a concern, and the practice was suppressed in 1911. Since then, combustion in furnaces was the disposal method in practice. By the middle of the Century the open dumps were still active and recognized. The practice of incineration in houses started taking place in 1907, but was banned in 1976 due to its resulting high levels of pollution.

With the uncontrolled incineration considered a hazardous disposal method, a new system was created: the landfill. In July 1977 lands in the Coast of the Plata River and Reconquista basin were reserved to implement the landfills. A company to manage the operations was also created, the '*Coordinación Ecológico Área Metropolitana Sociedad del Estado'* or CEAMSE.[25]

CEAMSE is the largest waste management company in Argentina. It is a government agency that reports both to the Province and the City. CBA and its 24 adjacent municipalities (the Metropolitan area) are growing continuously. Therefore, it was necessary to create a waste management company between the City and the Metropolitan Area, and this is how CEAMSE was founded in 1978.

4.3 Buenos Aires' MSW

4.3.1 Production rate

The City of Buenos Aires produces 4,730tn/d of MSW[21] which divided by its population gives a MSW production of 0.597tn per capita. Statistics show that in 2009, the MSW was produced 50% by households, 7% by street cleaning, and 43% by big generators (public and private) and dry goods.[33] All of the statistics and studies on waste in the City of Buenos Aires are based on the waste received at the transfer stations of the municipality. This means that the portion collected by the *cartoneros* is not being considered. No official data exists on the amount collected by them – this topic will be developed in more detail in section 4.5.1. However, it is estimated that the amount corresponds to 36,000 metric tons per year.[36]

There is practically no seasonal effect on the MSW generation. Its rate does not vary much during the year, with the exception of the Christmas and Easter periods where there is a slight increase.[26]

4.3.2 Characterization

In order to have a better understanding of the waste that is being disposed of, below are listed the types of streams that can be found in the landfill:

- Municipal and industrial that can be added to the municipal (similar composition)
- Analyzed solids and sludge
- Treated special waste
- Treated pathogenic waste – not ashes
- Ashes from the incineration of pathogenic waste
- Ashes from the incineration of industrial waste
- Green waste (pruned and organics from the fairs and markets, for composting). Composting plant capacity: 600tn/month
- Waste with asbestos

The MSW production varies according to the economic situation of the different sectors of the population[27]. Specifically in the City of Buenos Aires, the following correlation has been developed by the Institute of Sanitary Engineering from the University of Buenos Aires:

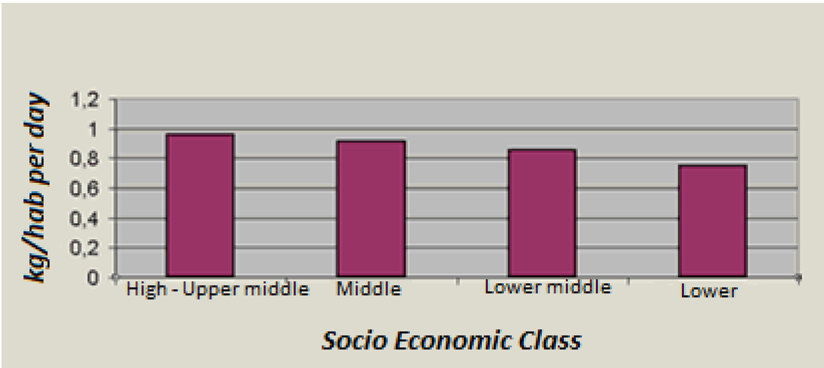

Figure 6 - MSW generation rates according to socio - economic class[21]

And, according to land usage:

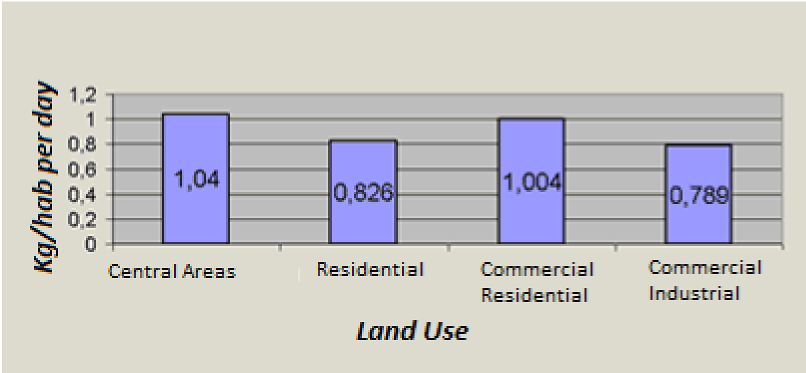

Figure 7 - MSW generation rates according to land use[21]

Consistently, Figure 8 and Table 5 show the strong relationship between the variation on the waste received by CEAMSE and the waste produced by Buenos Aires with according to financial stratum, represented by the GDP. An increment on the waste reception in 1990/1991 is observed due to the proliferation of cholera in those years, which decreased the MSW disposal into open dumps and increased the amount received by CEAMSE. Another factor is that after the devaluation of the Argentinean currency in 2001 and the following deep economic crisis, the GDP decreased by 12% in 2002 while the MSW treated by CEAMSE declined by 20%. An explanation for this is that the economic crisis also reached the municipalities, who opted for cheaper disposal to open dumps for 1 peso per ton as opposed to CEAMSE landfills that where charging 10.71 pesos instead.[33]

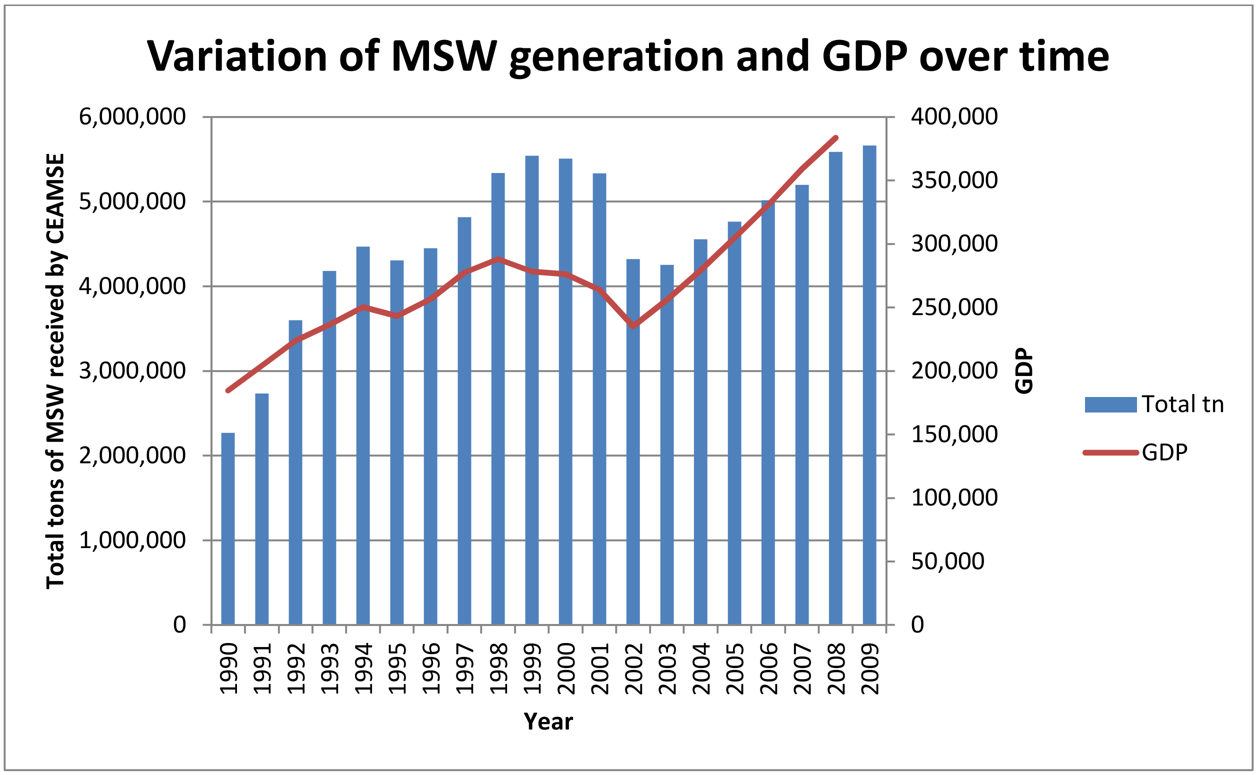

Figure 8 - Relationship of the variation of MSW production with GDP over time33[33]

Year	GDP	CEAMSE Tn	CBA Tn
1990	184,549	2,269,521	1,014,283
1991	204,067	2,733,924	1,207,140
1992	223,733	3,597,806	1,391,961
1993	236,505	4,180,086	1,504,422
1994	250,308	4,468,943	1,645,081
1995	243,186	4,303,997	1,514,011
1996	256,626	4,449,526	1,590,755
1997	277,441	4,814,861	1,671,849
1998	288,123	5,336,636	1,817,550
1999	278,320	5,541,015	1,997,253
2000	276,173	5,506,769	1,953,375
2001	263,997	5,332,511	1,835,934
2002	235,236	4,320,176	1,443,047
2003	256,023	4,254,779	1,421,842
2004	279,141	4,555,373	1,492,867
2005	304,764	4,761,662	1,477,147
2006	330,565	5,016,893	1,536,453
2007	359,170	5,198,072	1,645,368
2008	383,444	5,585,210	1,844,003
2009	N/D	5,662,343	1,847,748

Table 5- MSW Received by CEAMSE and produced by CBA and GDP data over time[33]

With regard to the waste composition, Figure 9 and Table 6 show the percentages of each main type of component that comprises the MSW.

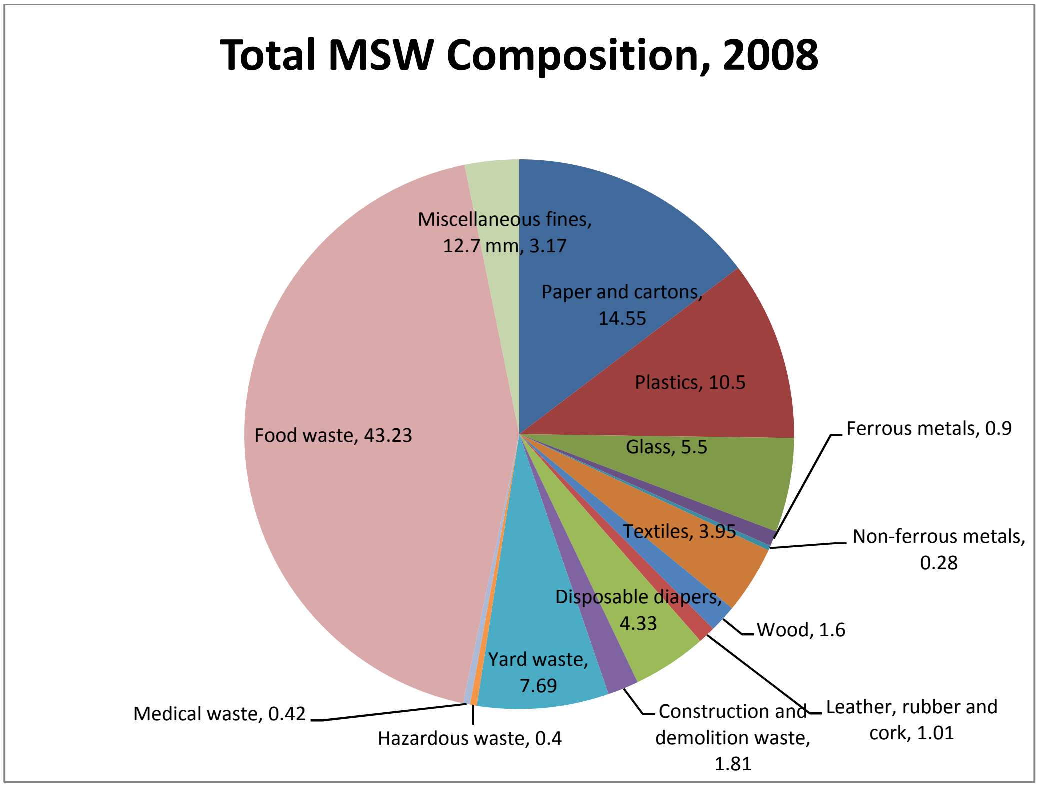

Figure 9 - Buenos Aires' MSW composition

Components	2005	2006	2007	2008	Average
Paper and cartons	18.24	17.15	16.32	14.55	16.57
Plastics	19.14	13.07	20.95	10.5	15.92
Glass	5.59	5.81	5.48	5.5	5.6
Ferrous metals	1.29	0.96	1.91	0.9	1.27
Non-ferrous metals	0.35	0.42	0.38	0.28	0.36
Textiles	2.74	3.9	3.38	3.95	3.49
Wood	1.15	1.08	1.56	1.6	1.35
Leather, rubber and cork	0.75	0.63	1.96	1.01	1.09
Disposable diapers	4.58	4.52	3.34	4.33	4.19
Construction and demolition waste	1.08	2.52	1.26	1.81	1.67
Yard waste	1.38	3.34	4.05	7.69	4.12
Hazardous waste	0.73	0.93	0	0.4	0.52
Medical waste	0.28	0.73	0.21	0.42	0.41
Food waste	37.74	41.28	35.76	43.23	39.5
Miscellaneous fines, 12.7 mm	4.59	3.59	3.03	3.17	3.6

Table 6 - Buenos Aires' MSW composition evolution by year[21]

As shown in Table 6, the composition of the MSW varies with time. Waste composition is a reflection of the consuming habits and economic resources of the population, varying through the different regions and countries. The wealthier population will have a higher concentration of dry components in their waste, whereas the poorer areas will have more organics and therefore humidity, since their waste is mostly composed by food desecrates. This is how we can interpret the differences in waste composition throughout the different areas of the City of Buenos Aires (values in Table 6 are total averages).

Based on the composition data, estimations of the heat capacity and the humidity content were calculated ponderating average experimental values from Themelis, Kim and Brady studies[28] of the three main components of the waste as follows:

Component	Energy Content (kJ/kg)	Humidity Content (%)
Food waste	3,500	75
Plastics	32,800	2
Papers and cardboard	16,500	7

Table 7 - Average experimental values of energy and humidity contents for MSW components

These values were also compared to the Tchobanoglous[29] tables, resulting in similar amounts, with consistent orders. Therefore, it can be concluded that the results reached are reasonable estimations.

Calculated values	Year 2005	Year 2008
Heat Content (MJ/kg)	13.9	10.8
Humidity Content (%)	40.6	49.3

Table 8 - Calculated values of heat and humidity content for MSW in CBA in 2005 and 2008

Table 8 shows the variation of the heat and humidity contents over the years. This phenomenon is a result of the variation of the MSW collected in the city due to informal recycling, which decreases the percentage of plastics, papers and cardboard, consequently decreasing the heat content and increasing the humidity. Conversely, the studies performed by Prof. De Luca[30] show that MSW ranges from 52% in the spring of 2007 to 54.7% during the summers of 2005 and 2006, up to a high content of 59.5% in the winter of 2006. The high calorific value during the 2005-2007 period ranged from 11.8 to 14.6 MJ/kg, which would correspond to a Low Heating Value (LHV) of 10.6 to 13 MJ/kg. Even though, Prof. de Luca clarified that these values may be too high and not representative of typical CBA MSW, they do actually match in magnitude the estimated values shown on Table 8.

The statistics also show that the average density of the MSW in 2008 was 282.75 kg/m3, and 236.36 kg/m3 in 2009. The percentage of recyclables is 15.7%, that is 416 tn/day.[21] However, this number does not include the recyclables originally collected informally, which amount is estimated to be of about 36,000 metric tons per year as will be developed in detail in Section 4.5.1.[36]

When analyzing the waste composition we need to highlight that 17% (that is 16,244) of the industries in the country are located in CBA – that is an average of 12.2 people per industry (compared to 11.4 in the rest of the country). The predominant industries are: clothes (15.7%), food (12.5%), graphic prints (12.5%), metal products (8.4%), machinery (5.3%), furniture (5.9%), plastics (4%), and leather (4%). This structure is obviously also influential on the MSW composition.

4.4 Legal framework

Various regulations dominate the waste management in the region, from the National Constitution to local by-laws. With the Constitutional reform of 1994, Article 41 was enacted with provides that the Nation has to set the minimum budgets, and the Provinces can then supplement them without violating any of the National regulations. Under this framework, General Environmental Law No. 25,675/02, Industrial Waste Law No. 25,612/0291, and Household Waste Management Law No. 25,916/04 were approved, establishing the minimum requirements to be complied with throughout the Country. Besides generally establishing the minimum budgets, the laws specifically provided as follows: (i) Law No. 25,675 sets forth the coordination between National, Provincial, and Municipal laws; (ii) Law No. 25,612 sets forth the different risk levels of industrial waste and provides the minimum requirements for the generators, the technologies, the registries, transportation, treatment plants and final disposal, and civil responsibility, etc.;. and (iii) Law No. 25,916 of Environmental Protection for the Integral Management of Solid Waste sets forth the minimum budget for waste management in the provinces, the proper management comprising the entire circuit of it - considering its value and final disposition -, and the inter-jurisdictional methods.

Additionally, the City of Buenos Aires and the Province established their own stricter regulations. This is how the CBA Province sanctioned Law 13,592 dictating that every municipality has to present their own integral SWM program, including the close up of open dumps and their replacement for landfills.

One of the most relevant edicts in CBA is Law No. 1854, also known as the 'Zero Waste Law' (*ley de basura cero).* Approved in November 2005 and enacted in May 2007, the law sets forth the ambitious goal of reducing the quantity of waste produced in 2004 by 75% by the year 2017. Moreover, it establishes progressive steps aiming to reduce levels 30% by 2010, 50% by 2012, and bans the final disposal of any recyclable or reusable waste by 2020. Besides, Article No. 7 prohibits the combustion with or without energy extraction of the City's MSW as a final disposal method, regardless of the location of the plant (in or outside the city).

Type	2008	2007	% 08 vs 07
Households	778,502	831,212	-6.30%
Streets	116,362	186,555	-37.60%
Others	949,154	627,601	51.20%
TOTAL	1,844,018	1,645,368	12.10%

Table 9 - MSW reception by CEAMSE in 2007 and 2008 [31]

Even though Table 9 indicates that the MSW received by CEAMSE increased by 12.10% from 2007 and 2008, very far from the objectives established by the zero waste law, Table 8 shows that in actuality, there was a decrease in the MSW generated in the streets and by households. However, the decrease, was more than offset by the increase of 'others' resulting into a net increment of MSW reception. To be more specific, 'others' represent big residues, waste from construction, fallen trees, and others. The significant increase of this category of MSW is caused not only by an increase in the construction work during the year, but also –and mainly – because other alternative sites used in the disposition of this type of waste reached their maximum capacity and had to be closed. Regardless of the reason why the overall MSW production increased, it is a fact that the production rate has not decreased over the last years (although it has stopped increasing), and it is significant to point out that in some well developed countries it has taken nearly 25 years of educational campaigns to obtain a recycling rate of between 20 and 35%.

Furthermore, Exhibit A presents the results of a survey conducted on 200 Buenos Aires residents out of which over 80% are professionals or students, representing a generally educated pool of citizens. When they were asked how much they knew about the zero waste law on a scale 1 to 5 (1 in place of no knowledge and 5 in place of knowledgeable), 66% responded 1. Figure 10 shows the totality of responses obtained. What's more, when they were asked if they recycle, only 19.1% gave a positive response. Based on these results and previous cases of other nations, the objective of reducing 30% over 5 years and 50% in only 2 years more is unlikely to be realistic.

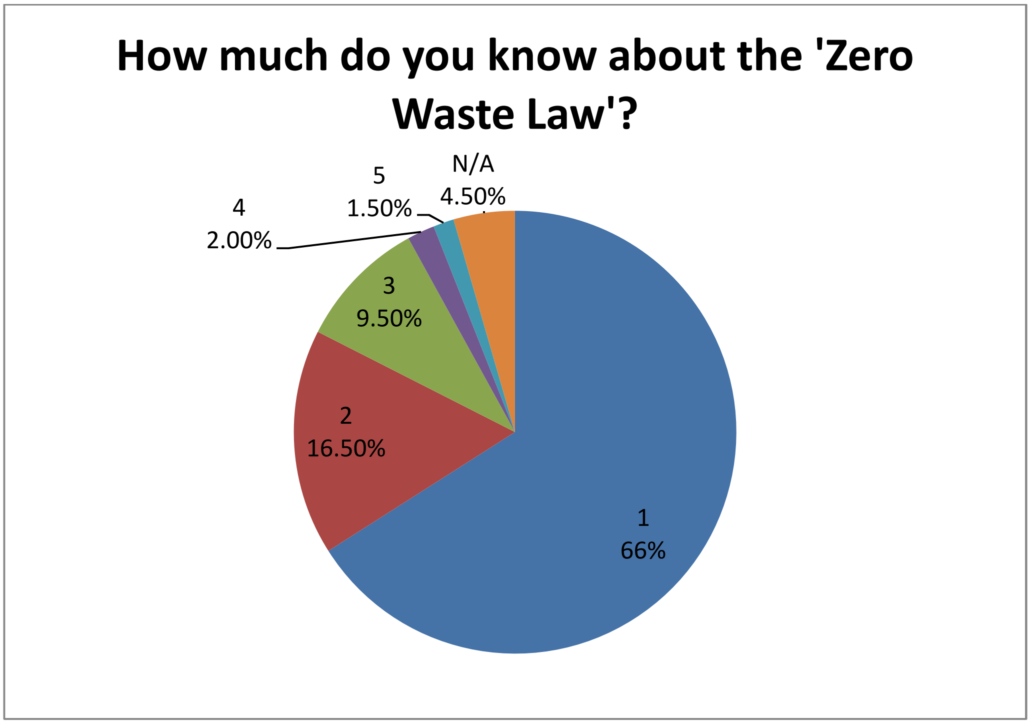

Figure 10 - Knowledge of the population of Buenos Aires regarding the 'Zero Waste Law', on a scale 1 to 5. 1 Represents no knowledge, 5 represents knowledgeable[32]

A second relevant regulation is Law No. 992, approved on December 12, 2002. The law establishes that the Executive branch of the government has the primary responsibility to launch a public policy oriented to implement an integral SWM system in the CBA, aiming to preserve the environmental resources and improve the working conditions of the informal waste collectors (*cartoneros*). As part of the policy, an educational campaign to citizens on recycling is included, as well as the design of a separation plan in the origin.

The following are the additional principal existing National, Provincial and Urban laws related to solid waste management, coordinated by the ENGIRSU (National Strategy for the Integral Management of the Urban Solid Waste).

- Law No. 26,011: The Stockholm Convention – *on persistent organic pollutants*.
- Law No. 25,831: Free access to the public environmental information regime. *Establishes the entities with obligations and their corresponding procedures.*
- Law No. 22,428: Fomentation of soil conservation. *It declares of general interest the private and public action to conserve and recover the production capacity of the soil.*
- Law No. 20,284: Air resources preservation. *Contains the air quality standards.*
- Law No. 24,051 and decree Regulation 831/93 (B.O. 27.307 of the 17/01/92): Hazardous Waste. *Defines hazardous waste and establishes how to handle and dispose of them.*
- Constitution of the Province of Buenos Aires Art. 28. *Provides that the citizens have the obligation to preserve the environment.*
- Resolution Nº 601/98 of the Environmental Policy Secretary (24/11/98): Entrance of Toxic Residuals. *Defines toxic residuals.*
- Law No. 11,720 (B.O. 13/12/95) and decree Regulation 806/97 (16/4/97): Special Residuals. Establishes the generation, manipulation, storage, transport, treatment, and final disposal of special residuals in the Province of Buenos Aires.
- Law No. 11,737: modification of the Law 11.175. *Designates the Environmental Policies Secretary as Authority of Application of the Laws 11,347; 11,459 and 11,720*
- Decree Law 9,111/78L Regulates the Final Disposal of Residuals in the Province of Buenos Aires.
- Law No. 11,723: Protection of the Atmosphere. *Observed law for Ordinance 4371/95*
- Law No. 11,382: Modification of the Ordinance Law 8,031 / 73.
- MUNICIPAL ORDINANCE 39,025 (B.M. 17.049 - published on the 13/6/83). *States the environmental obligations required for the industries.*
- Code of Prevention of the Environmental Contamination of the City of Buenos Aires
- Ordinance 33,581 (BM 15.540): Modified by Ordinances 33.681 (BM 15.575) and 38,188 (4/10/82) it modifies arts. 4, 6, and 7. *Lists the dispositions for the population of Buenos Aires to preserve the hygiene and neatness of the City.*
- Ordinance 33,691 (BM 15,577) Ratified by National Decree 3,457/77:

4.5 Solid Waste Management in Buenos Aires

4.5.1 Recycling: Formal and Informal

When referring to recycling, people tend to associate this word to what it is called ‘formal’ recycling, which is the process that occurs after the collection and typically involves some kind of separation plants. However, ‘informal’ recycling predominates in CBA over the formal.

As mentioned above, formal recycling engages some sort of separation. This process can be done completely thorough a separation plant –in which case is more costly – that can be manual, mechanic, or high tech; or it can start at origin, which will make the processing cheaper due to the sizing and complexity of the plant, by means of differential bags, containers, or any mixed system followed by an additional separation plant treatment since the previous step is usually not perfectly done for a number of reasons such as: the time that it takes to get the population more involved with a recycling program, the time it takes to improve the population's environmental education, human error, or simply a lack of interest and/or idleness.

Particularly in CBA, there are nine small recycling plants operated by the municipality and four private ones - only two in operation – where recyclables are sorted to marketable streams, mostly manually. It is estimated that approximately 60,000 metric tons of MSW per year are sent to separation plants for formal recycling. New plants for recyclable waste management - selection, separation, packaging, etc - are currently being developed, such as the new plant in Varela y Janer, under construction since 2010.[26]

Considering that the waste characterization studies presented in Section 4.3.2 estimated that over 15% of the MSW that is currently being landfilled could be recycled, the tonnage for recycling at present does not seem to be sufficient, and the percentage should be boosted. When planning a (formal) recycling procedure for the City, the collection system is a key component. For instance, it is pointless not only for the results, but also because the resulting perception from the population will discourage the separation, to educate people on how to separate at origin if the collection trucks will mix all the waste streams back together. In fact, in a survey of over 200 residents of Buenos Aires (see Exhibit A for the complete survey) 81.9% responded negatively when asked if they recycle. Moreover, when they were asked why they did not recycle 59.2% of that portion answered that the reason was that everything winds up mixed together in the collection trucks.

A key component of the recycling system in CBA is the informal recycling by individuals. This activity was substantially increased in 2002 as the effects of a deep economic crisis that hit Argentina, resulted in a currency and devaluation causing an increase in unemployment, poverty, and number of indigent people. As a result, the job market was completely frozen and it was very hard to find a job, either formal or informal. At the same time and because of the devaluation, the price in Argentinean pesos of certain commodities, such as paper and cardboard, increased substantially. The combination of these two factors resulted in the proliferation of the so-called '*cartoneros*'.

At that time, scavenging was forbidden by law; although this activity was legalized in January 2003 through Law 992 (See section 4.4) as a response to the explosive growth of this practice. The government intended to incorporate the *cartoneros* into the formal system. One of the biggest concerns was –and still is- that the *cartoneros* that operate on their own, without being a member of any association, usually leave the garbage bags broken on the street, which makes the city dirty, disturbs transit and blocks the storm sewers. On the other hand, if the work of the *cartoneros* was to be formalized, paying the corresponding benefits and taxes, providing uniforms, hygiene and safety elements, and even paying a fair price for the materials, the economic equation becomes impractical in most cases. [33]

The Mexican policy to address this issue has an interesting basis, developed by the Secretary of Social Development (*SEDESOL – Secretaria de Desarrollo Social*): Even though the MSW disposed of on the streets generates thousands of jobs for the Mexicans, it is necessary to help them achieve independence, provide a decent future for their children, and improve their living conditions – economic situation, housing, health, and education. In addition, it is particularly important to withdraw the younger kids from this activity so that they do not consider following these actions later on.

Even though there are no official statistics regarding the number or characteristics of the *cartoneros* currently operating in the City, it is estimated that there may be as many as 5,000 to 9,000, which usually work in small groups. In the absence of official statistics, the tonnage collected by these people was estimated to be about 36,000 metric tons per year[3626], which is about 2% of the amount landfilled in the three landfills of Buenos Aires. In total, the current recycling rate was stated to be less than 6%. Nevertheless, other sources such as studies from the Government Department of Urban Recycling Policies (*Dirección General de Políticas de Reciclado Urbano, or 'DGPRU'*) affirm that 11% of the MSW – considering both households and street cleaning - is being recovered. The University of Buenos Aires on the other hand, argues that the amount is between 250 and 300 tons per day, which is somewhere in between 11 and 13% but as to the household waste only, it is estimated to be 2,678 tons per day, or 0.359 tons per capita.

4.5.2 Composting

In the surroundings of the landfill there is also a composting facility that composts green waste aerobically. An estimated 15,000 tons of compost per year is produced and used for landfill maintenance. The compost is used within the landfill.[26]

4.5.3 Landfilling

Acceso Norte III is the biggest Landfill in the area, and its remaining capacity is estimated to be used up by the end of 2012. Therefore, new solutions and upgrades are continuously required. A project for energy generation out of LFG has been approved and is now under construction.

Located in the North-West of the City of Buenos Aires as shown in Figure 12, Acceso Norte III Landfill not only serves the totality of the population of the city of Buenos Aires, but also the following localities: Almirante Brown, Avellaneda, Berazategui, Escobar, Esteban Echeverría, Ezeiza, Fcio. Varela, Gral. Rodríguez, Gral. San Martín, Hurlingham, Ituzaingó, José C. Paz, Lanús, Lomas de Zamora, Malvinas Argentinas, Merlo, Moreno, Morón, Pilar, Presidente Perón, Quilmes, San Fernando, San Isidro, San Miguel, Tigre, Tres de Febrero, and Vicente López. This means that even if the facility is originally designed to serve only the population of the City of Buenos Aires, its capacity can then be extended in order to serve any of these other places as well.

Currently, the Acceso Norte III landfill serves 14 million inhabitants, takes in about 489,000 tons per month (5.87 million tons per year) of MSW, and receives 89.9% of the waste generated in the Metropolitan area. Additionally, the landfill receives about 6,200 tons/per day from the three WTS of the City of Bs As, and 1,000 tons from the other municipalities. Owned and operated by CEAMSE, the landfill is equipped with leachate treatment facilities and with the equipment necessary to effectuate a partial capture of LFG that is currently flared.[26]

Acceso Norte III is formed by three closed modules and a fourth one that is currently operating. The closed cells are maintained with grass, bushes, and small trees growing on them. Details of these modules are presented in Table 10. The maximum landfill height was estimated at 35 meters. A previous statistic from the Earth Engineering Center of Columbia University determined that approximately one square meter of green field is converted to landfill for every 10 tons of MSW landfilled, based on the US Environmental Protection Agency specification to use a 15 centimeter daily cover of soil. The calculated metric tonnage per square meter shown in Table 10 shows a higher capacity, which is believed to be because of the use of a different amount of soil cover than the amount stipulated by the US EPA.

Module	Start Date	End Date	Area (Ha)	MSW disposed (Tn)	Tons per square meter
Norte III	Oct, 1994	Dec, 2001	64	10,501,269	16
Norte III a	12/1/2001	2/11/2006	64	10,944,878	17
Norte III b	12/1/2005	2/11/2006	84	14,054,675	17
Norte III c	4/5/2008	Operating	-	11,294,228	-

Table 10 - Characterization of the Modules that constitute Acceso Norte III[26]

4.5.4 Collection

For the purpose of collecting MSW, the city is divided into six areas, which limits can be appreciated in Figure 11. The service is currently performed by 2,500[35] employees who work in five companies: Cliba, Urbasur, Aesa, Níttida e Integra, each of them in charge of one of the mentioned areas, and the sixth area is under the Government's management. The Municipality intends to keep a portion of the provision of this service so that under contingencies or emergency situations, they can still provide these services, at least partially. There are 226 routes along the city which paths can be seen in Figure 11.There are approximately 1,000 collection trips from the streets to the transfer stations a day necessary to accomplish the collection all over the city. [34]

Having presented the current situation, it is also appropriate to mention that there is an open bid to provide a new collection service in the city. This new system would separate the waste into two streams, a wet one and the dry one, that would be collected separately. With regard to the wet stream collection only, the city would be re-divided into four zones as opposed to the current six. As for the dry stream collection, the city would be divided into fifteen areas and the waste would be picked up by actors of the informal sector who will be competing for the job.[35] [26]

In order to implement the new collection system, beginning in 2007 the city has taken action to progressively acquire containers along its territory to receive the dry and wet waste separately. Over 9,000[21] containers were installed in 2009. The containerized routes are shown in Figure 12.

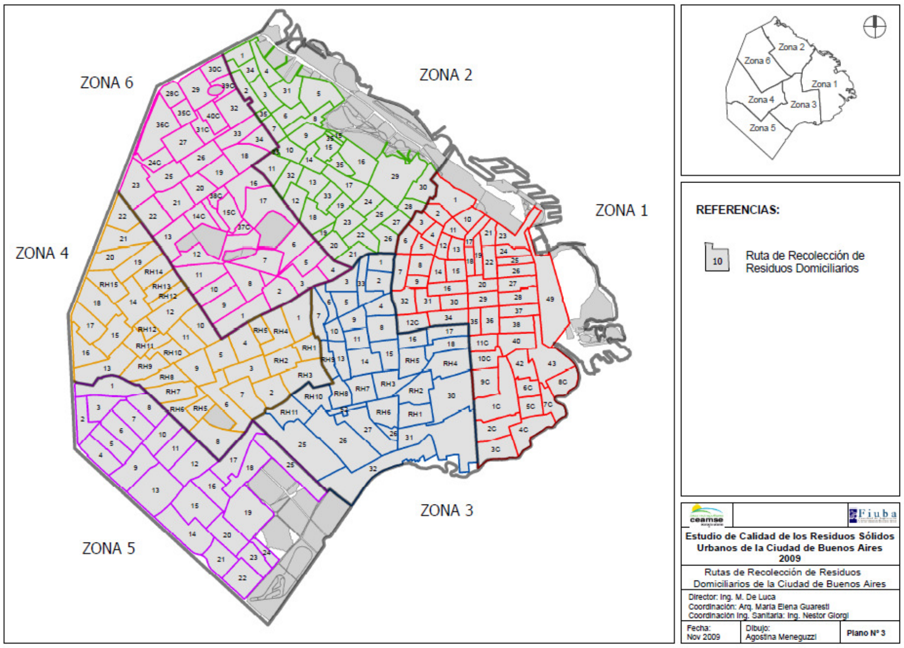

Figure 11 - Collection routes[21]

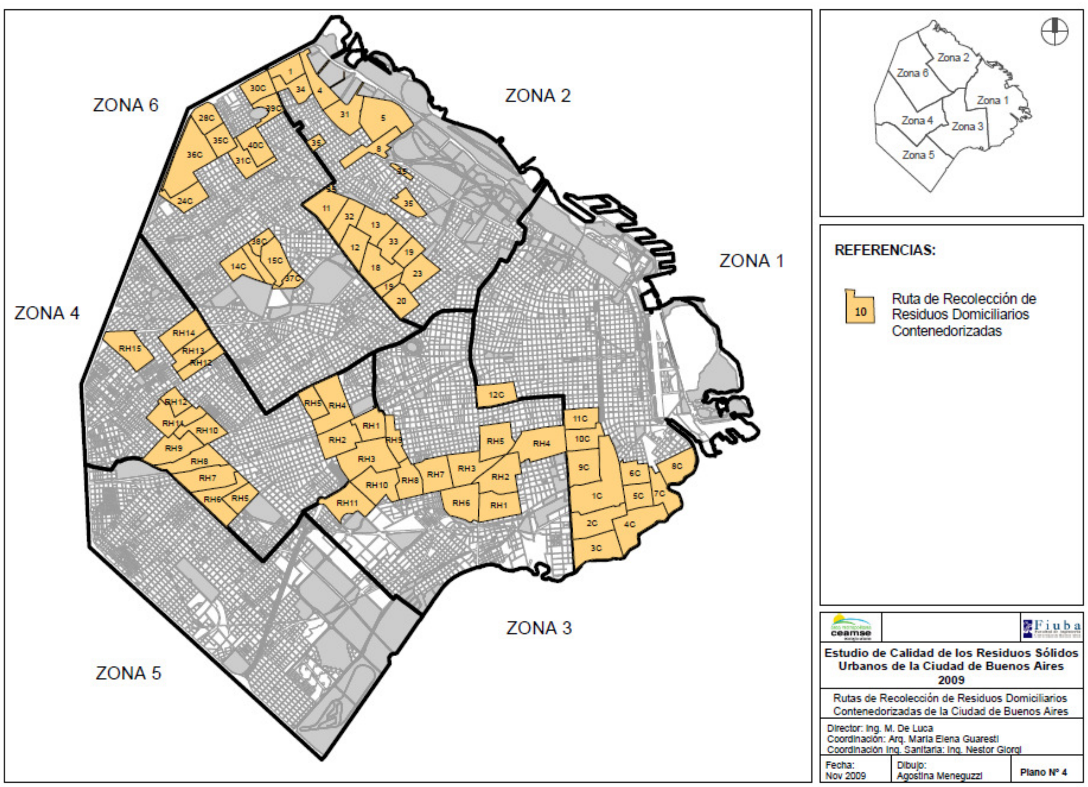

Figure 12 - Containarized MSW Collection routes[21]

4.5.5 Transfer stations

Three waste transfer stations (WTS) operate in CBA, located in Pompeya, Flores, and Colegiales, each handling approximately 65,000 metric tons of MSW per month and estimated to have sufficient capacity for future years.

As Figure 13 and Figure 14 evidence, the furthest WTS from the landfill is in the eastern part of the City - Estacion de Transferencia Pompeya; 22.7 km from Norte III "as the crow flies". The WTS Flores is directly west from Pompeya -18.5 km from Norte III.

The closest WTS to the landfill, Colegiales, is in the northern part of the city 15.7 km away from landfill, and is located in the middle of a fairly well-to-do area of the city. Despite the fact that this transfer station was built in 1979, it is very well designed and operated. Across its fence is a public park with playing fields. There is no dumping of MSW on the floor, and therefore no detectable odors as is the case with several waste transfer stations in New York City. The collection trucks drive up a ramp and dump their load in a horizontal bin. A piston mechanism then pushes and compacts the MSW into the container of the large trucks that then transport it to the landfill. The capital cost of this WTS was estimated at $10 million, not including the cost of the land.[36]

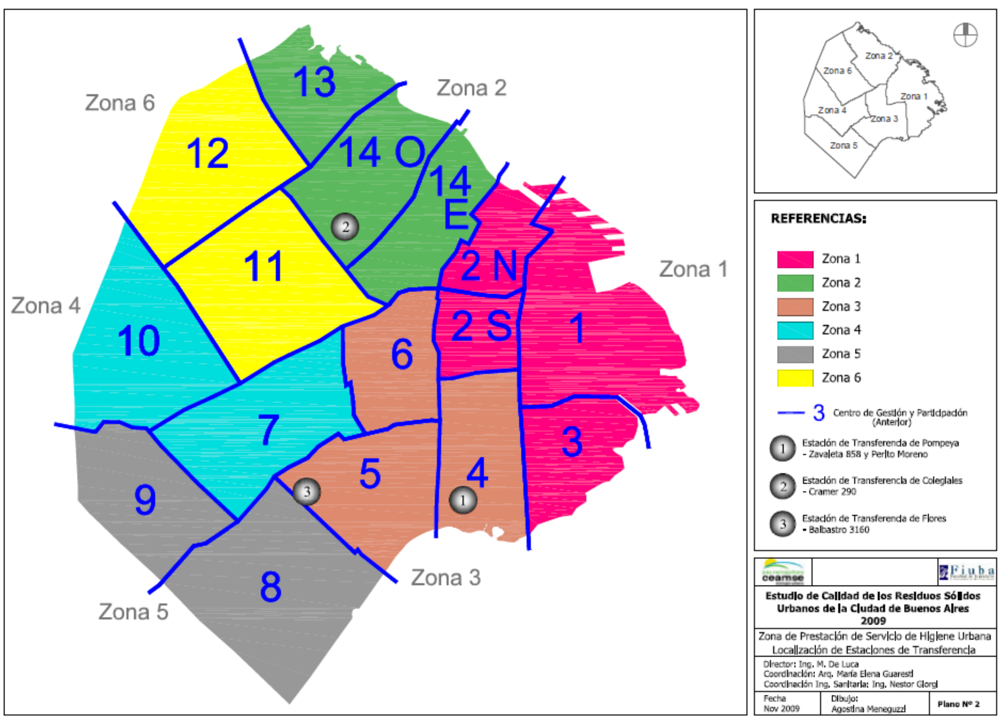

Figure 13 - Map of the 6 zones of CBA, and location of the transfer sations[21]

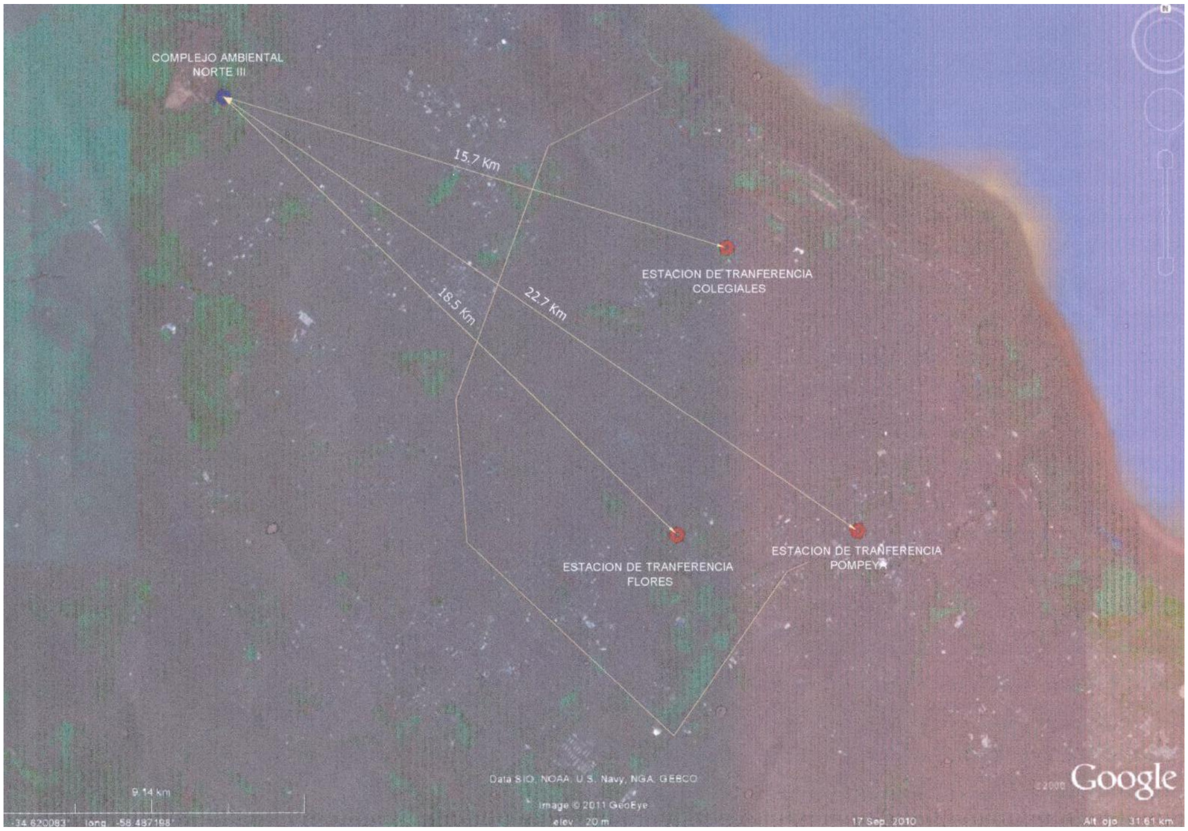

Figure 14 - Map of the location of the Acceso Norte III with respect to the 3 transfer stations[36]

4.6 Waste-to Energy in Buenos Aires

As presented before in Section 3.2, the phenomenon 'not in my backyard' in addition to the constantly growing population of CBA and correlating constant expansion of the city over time resulting in increases to the land prices closer to the city, makes it increasingly necessary from a fixed cost perspective to locate the landfills further away, despite increasing the costs and greenhouse gas emissions associated with the transportation of the MSW. On the other hand, this fact also represents an opportunity to implement Waste-to-Energy plants. WTE takes considerably less space than a landfill, and could even be located in the middle of the city if it was necessary (as is in Vienna).

There are currently no WTE facilities in Buenos Aires or in the rest of the country. WTE is presented in this work as a proposed partial solution to the SWM crisis in Buenos Aires City.

Because a plant takes much less place than a landfill, the WTE facility could be located even in the middle of the city. The main advantage of this site is that it requires much less transportation thereby cutting down the expenses from the most costly stage of the MSW circuit, and reducing the greenhouse gas emissions emitted. Moreover, the transfer stations could be eliminated since their purpose would be defeated.

Despite these advantages, the proposed facility would be located next to the landfill Norte III, without producing any significant changes in the collection routes and the use of transfer station. This decision was mainly based on the regulations, which are generally more restraining in the city – that is, regardless of the Zero Waste law, which bans the incineration of the MSW generated in the city in or out of its limits. Another reality that factors into the location decision is that even though the modern WTE technologies have very little impact to the environment, the public opinion generally starts off negatively when implementing any new industry, specially related to waste. It is believed that the neighbors' resistance would be much stronger in the City – particularly considering that no WTE plants were ever installed in the Argentinean territory before – than in the Province. In reality, the decision as per the location of the plant will be driven by the required location, specific regulatory compliance, and an extended financial-economic balance that considers the costs associated with the land, collection, taxation, and delivery of the final product (not only the ash, but even more importantly the energy produced).

As previously mentioned, the chosen location is at the Acceso Norte III landfill. Figure 15 and Figure 16 show the exact location defined by its geodesic coordinates. This landfill is the biggest one in the area, with a fostering active interest in implementing offset projects associated to it. The WTE facility could also be an offset project that will generate relevant amounts of carbon credits to support the financing of the plant. In fact, a project that converts the LFG from Norte III into energy was recently approved. The project will be connected to the grid to provide for its proper delivery. This is a major topic when considering the location of the WTE plant as well, since developing a grid specifically for the proposed facility would be too expensive and probably unrealistic.[37] On the contrary, the WTE facility would be using the electricity grid from the LFG project to deliver electricity. Currently, the distance from this site to the nearest power transmission line is three kilometers.**Error! Bookmark not defined.** Another alternative would also be to provide thermal energy, or even electricity to the industries located in the surrounding area as opposed to delivering it through the grid.

On the subject of capacity, It is recommended that the new facility be restricted solely for the use of the city in the beginning. According to Ms. Ana Corbi, Executive Director of the Provincial Organization for Sustainable Development (OPDS), the proposed WTE facility should only serve the City. With this purpose, a three-line 3,000 tn/day – or about 1 Mtn per year –MSW treatment WTE plant along with an increased recycling rate would serve the City adequately. With this capacity, it is estimated that the facility would deliver 0.7 MWh per ton of MSW (about 700,000 MWh per year), which would require a turbine of 100MW nominal capacity. The net power delivered to the grid would be of 88 MW.

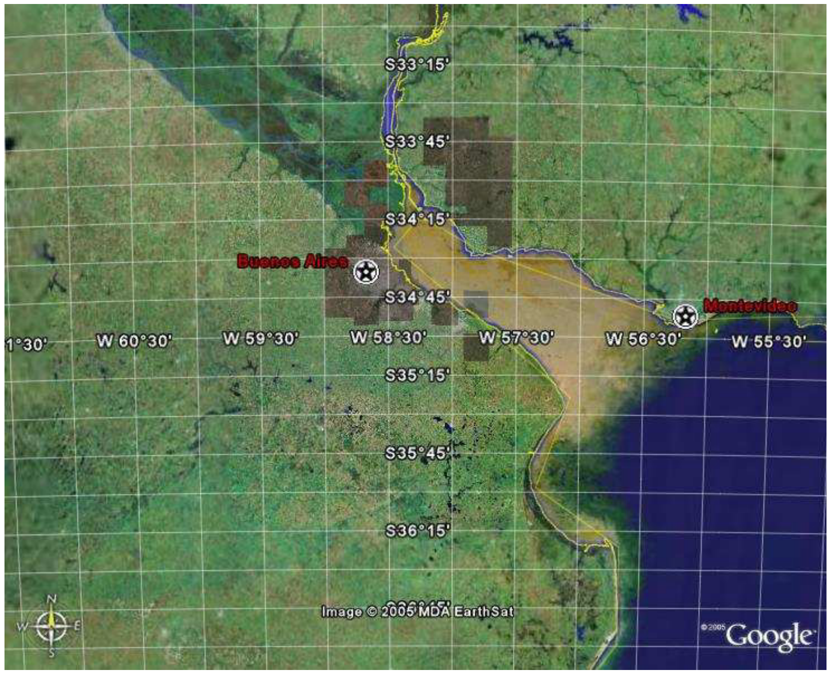

Figure 15 - Coordinates of the City of Buenos Aires[38]

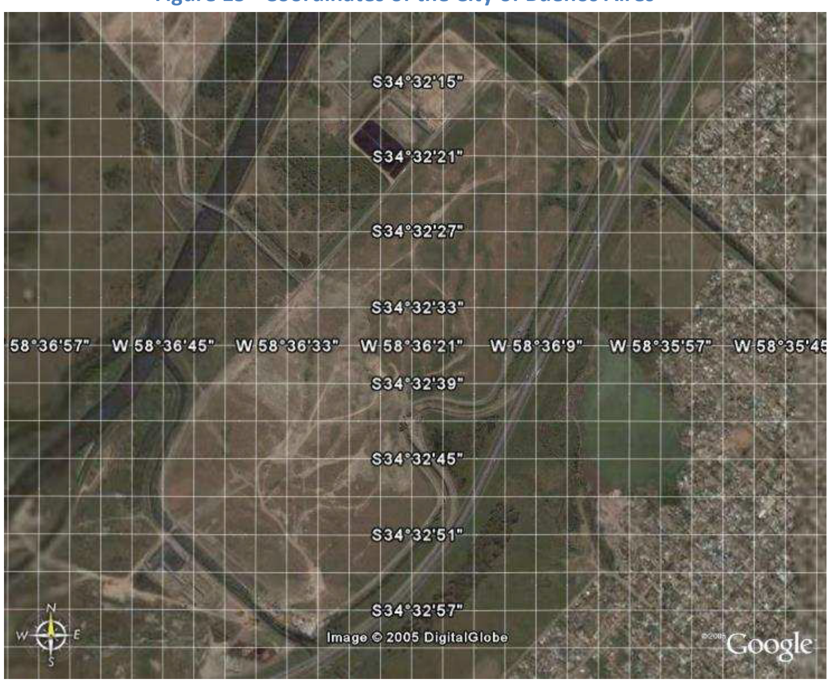

Figure 16 - Coordinates of the Acceso Norte III landfill [38]

5. Renewable Energies

5.1 Overview

WTE represents an advantage from both the waste management point of view as well as for energy efficiency, while also providing beneficial environmental effects (particularly greenhouse gas emissions) at the same time. As much of an advantage that WTE represents for CBA in terms of space savings, there is also a growing interest in the country on alternative energy generated out of MSW.

A recent project developed by the Ministry of Energy to determine the problems encountered when developing alternative energy[39] resources in the country was financed by the 'Renewable Energy and Energy Efficiency Partnership' (REEEP). In fact, they state on their web-site that one of the objectives of this project was 'to provide better information on natural resources and projects, especially initiatives on biomass residues'.[40] More specifically, the document expresses that there is an interest in stimulating the production of Energy out of MSW, particularly in the city of Buenos Aires. The project identified the principal barriers for the development of renewable sources of energies to be political, financial, regulatory, technologic, and social, in order of relevance.

As concerns technologies, the ones that were used and considered were gasification and pyrolysis, both followed by reforming with vapor. The main advantage to these technologies is that they allow the production of biofuels, one of the main alternative energy sources in the country. There also appears to be an intention to stimulate not only the electricity production, but also the thermal applications of these alternative resources.

GENREN is a program that was announced by the Secretary of Energy Daniel Camerón in May 2009. This Project is implemented through ENARSA (*Energía Argentina Sociedad Anónima*) with the objective to encourage the development of electricity generation out of renewable resources so that the sustainable development of the renewable energies gets strengthened across the country. GENREN expresses its intent to meet an ambitious production of 120MW from MSW.

5.2 Legal framework

Three are the main regulations relevant to the alternative fuels scenario in Argentina that would affect the provision of energy out of the WTE facility, and therefore deserve to be presented in the present text.

First, Law No. 24,065, which defines the regimen of electrical energy. This regulation is the most relevant to this work because it establishes the pricing of electricity, which will determine the pricing requirements of the electricity produced at the facility and consequently influence the tip fee for the MSW reception at the WTE facility. See section 5.3 for information on electricity prices.

Second, Law No. 26,190, also called National Law of Renewable Energies. Article No. 2 establishes the National goal to supply 8% of the energy in the country from renewable resources by 2016. Since WTE is a renewable energy source, the development of the WTE plant will also contribute to the interests of the energy side as it will contribute towards the achievement of this goal.

Third, Resolution 1281/2006 particularly Article No. 2 declares the existence of the 'Energy Plus Service' The program forces big industries to supply for their own the extra energy that they consumed with respect to 2005. It also supports the increments of individual users by promoting the rational use of the energy and encouraging the self generation and cogeneration. The resolution can also be translated as the allowance to surcharge the consumers for any extra energy consumed with respect to 2005. This represents a potential benefit for the WTE facility, since the generated electricity could serve the requirements of this program by providing peak energy and at a higher price, as it will be explained in the following Section 5.4.

5.3 Electricity price

There are two companies that provide electricity to the entire CBA: EdeNor (providing electricity to the northern part of the city) and EdeSur (providing electricity to the southern area of the city). The service provision is by default according to the location of the dwelling or commerce. The State's contract with these companies is included in Law No. 24065. The price for the kWh is also established therein, under Subannex 1.

For pricing purposes, the law classifies the consumers into low demand (maximum demand below 10 kW), medium demand (maximum average demand over 15 consecutive minutes is between 10 and 50 kW), and high demand (maximum average demand over 15 consecutive minutes is over 50 kW). Exhibit II shows the regulated fee tables according to the described categories. It is important to highlight that the pricing of the kWh is strongly subsidized by the Government.

There is no information on the price projection of the energy available. As for the projected energy production, the studies will be soon released to the public but are not yet available.

Despite the regulated prices for energy, different fees can be used for renewable energies. According to Ana Corbi, Executive Director of the Provincial Organization for Sustainable Development (OPDS), the value of renewable electricity can be between $100 and $120 per MWh.[41] The incentives available that allow the sustainable technologies to be competitive in the electricity market are presented in the next Section.

5.4 Incentives available

When it comes to the generation of renewable energy in Argentina, there are two ways to go to establish the price and receive incentives that would make the projects economically feasible.

The first approach is to increase the price of the energy produced through the '*Energía Plus*' program presented in Section 5.2. Under the objectives of this program, the plan allows a surcharge on the pricing of the electricity provided to consumers whose consumption exceeds the use of electricity during the year 2005.

The second approach is to obtain incentives through the renewable energies law, which establishes incentives for the investments and for the consumers. Article 14 of this law (No. 26,190) grants up to AR$0.015 per kWh for energy produced out of biomass, the category under which WTE would fall.

Regarding public financing options, there are several programs and institutions offering financing to alternative energy programs. Among them, the Global Environment Facility (GEF), whose projects for Argentina can be seen here http://www.thegef.org/gef/gef_country_prg/AR ; the National and the City's Government, who constantly release different programs to incentivize renewable energy generation; the ENARSA corporation (*Energía Argentina Sociedad Anónim*a), founded through National

Law No. 25943. New bids are regularly open related to renewable energies, which are published on their web-site (http://www.enarsa.com.ar/home_licitaciones.htm).

In addition to the above mentioned institutions web-sites, other routes of public communication are the '*Página 12'*, 'Ámbito *financiero'* and '*Cronista Comercial'* newspapers.

6. Cost Analysis

The financial and economic features of the WTE facility are drivers of its implementation, and therefore it is critical to include these aspects in the analysis. Because the costs constantly change, particularly considering the high inflation that affects the country, making a detailed cost analysis on the implementation of a WTE plant would be out of date as it is being developed, defeating the purpose. For that reason, the main subject matters will be presented with the purpose of providing guidance for a cost analysis that may be carried out in the future.

The gate fee is the price that the City of Buenos Aires pays a disposal facility such as a landfill or, in this case a WTE plant, to receive and treat a ton of MSW. The City of Buenos Aires currently pays CEAMSE a gate fee of about AR$20 per ton of waste, although the real cost of operating the landfill, including maintenance of closed cells is estimated at AR$20 as well. Moreover, the cost to operate the WTS and transportation of MSW to the landfill is estimated at approximately AR$22 per ton.[36]

Ideally, the gate fee is calculated considering a number of factors, including the initial investment, the operation costs, income from the energy sales, recovered metals, carbon credits, and revenues. But the first step is to define the costs boundaries. That is, deciding whether the collection, the WTS operation, and transportation from WTS to the facility costs will be included in the gate fee or if they will be segregated.

As regards the initial investment costs, they would consider the cost of the land, installation, technology, and start up. On the other hand, monthly expenses would include the costs of labor, equipment maintenance, utilities, material, ash disposal, environmental testing, transportation (if desired), WTS operation costs (if desired). The electricity price will be established based on the possibilities presented in the previous sections. Finally, since WTE generates greenhouse gas emissions offsets, it is likely to be eligible to apply for carbon credits.

In order to provide an idea of the magnitude of the offsets that can be generated, Figure 17 provides an estimation of the emissions produced by the Norte III landfill based on the deposited waste. The biogas to energy project that is currently installed by the landfill is a good example of a project that is now reporting its offsets to finance the costs of the project with the carbon credits.

Year	Deposited waste tn	Produced biogas estimation m^3/year	Produced CH_4 estimation tn/year	Baseline CO_{2e} estimation tn/year
2006	3,563,638	-	-	-
2007	3,586,498	-	-	-
2008	3,609,503	32,332,168	33,108	695,271
2009	3,632,657	46,818,502	47,942	1,006,785
2010	607,704	60,299,947	61,747	1,296,690
2011	-	58,521,336	59,926	1,258,443
2012	-	54,022,001	55,319	1,161,689
2013	-	49,868,593	51,065	1,072,374
2014	-	46,034,513	47,139	989,926
2015	-	42,495,211	43,515	913,817
2016	-	39,228,024	40,169	843,559
2017	-	36,212,031	37,081	778,704
Total	**15,000,000**	-	-	**10,017,258**

Figure 17 - Estimation of greenhouse gas emissions per year for the period of 2006 - 2017[37]

7. Conclusions

The current SWM system in Argentina is in crisis, particularly in the cities, where the high prices of the adjacent lands limits the closeness of the disposal sites to the conurbation. Since Buenos Aires and the Metropolitan Area generate 40% of the waste of the country and the landfill that receives 90% of this waste will reach full capacity in 2012, the improvement of Buenos Aires' SWM system is of significant relevance.

WTE is proposed as a solution to the crisis, one that would also be a significant factor in fostering a more sustainable city. The proposed WTE facility would be located next to the landfill, where a connection to the grid is available, and would provide several benefits to the SWM system: Less space to operate compared to a landfill, same distance to the city which avoids increased transportation costs, and the promotion of recycling. The latter is a controversial topic as many environmentalists would argue that WTE has the reverse effect – that is, that all of the waste would be burned instead of being recycled or composted. An example of this is the Zero Waste Law, which forbids WTE on the basis that it would have a counteracting effect on developing a strong recycling structure in CBA. However, actual results show that the cities that have WTE also have a high recycling rate (that is the case in Vienna and the cities in Japan that were previously presented). However, it is expected that the public opinion will be negative in the beginning. The author believes this is a matter of education, as indicated by question 9 of the Survey in Annex A, where it is observed that 45% of an educated sample of the population declares that it has absolutely no knowledge about WTE in its country. Nevertheless, an interesting observation is that when they were asked to rank the different final disposal methods of waste according to their perception of the risks they represent, WTE was ranked as less hazardous than landfills.

The ignorance of the population on MSW matters is also a concern that the city faces. An intense, structured, educational campaign on the issue is necessary to move on to the next step, particularly instructing the population on the separation of waste at origin. This would avoid the disposal of material that could be converted into valuable products.

Returning to the WTE facility, it would also bring additional benefits apart from the ones related to SWM, such as the delivery of renewable energy to the grid and the reduction of greenhouse gas emissions.

All in all, a strong education campaign to the populace on MSW matters, including recycling, along with the implementation of a WTE facility, would be the ideal way to establish a more sustainable city habitat for future generations.

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Exhibit A : Survey on Solid Waste Management

Survey pool: Citizens of the City of Buenos Aires

Pool Size: 200+

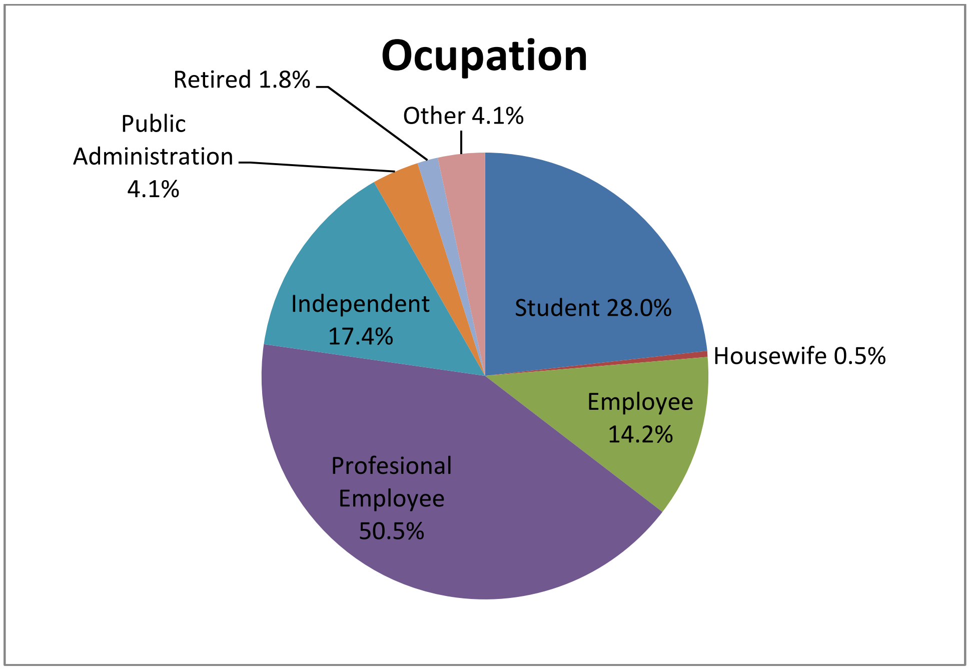
May 2011

Question 1: General Information

General Information		
Answer Options	**Response Percent**	**Response Count**
Sex	100.0%	218
Age	100.0%	218
Province	100.0%	218
City	100.0%	218
	answered question	**218**
	skipped question	**0**

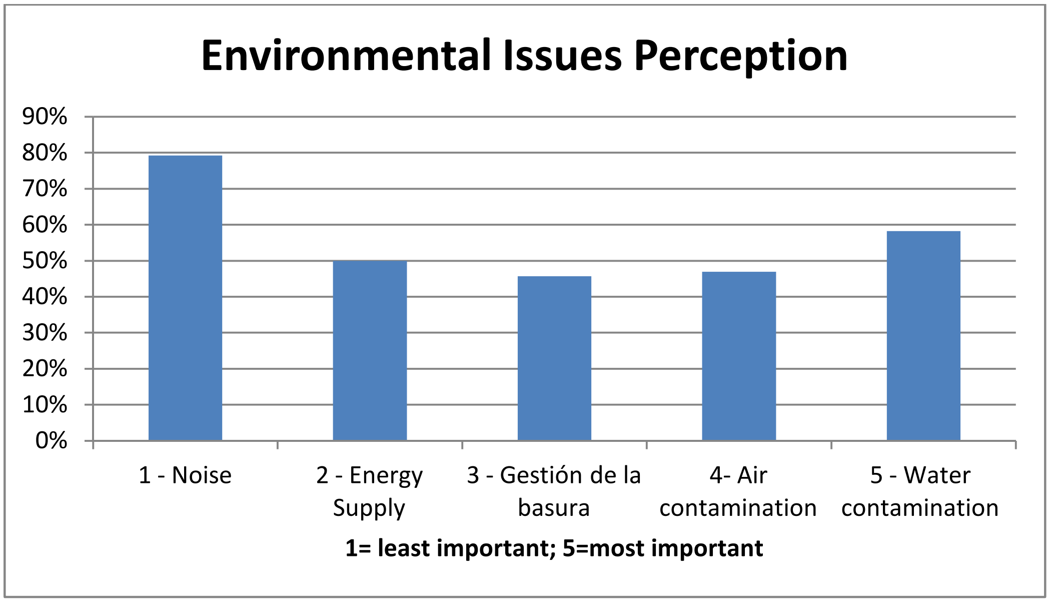
Question 2: Occupation

Occupation		
Answer Options	**Response Percent**	**Response Count**
Student	28.0%	61
House wife	0.5%	1
Employee	14.2%	31
Professional Employee	50.5%	110
Independent	17.4%	38
Public Administration	4.1%	9
Retired	1.8%	4
Other	4.1%	9
	answered question	**218**
	skipped question	**0**



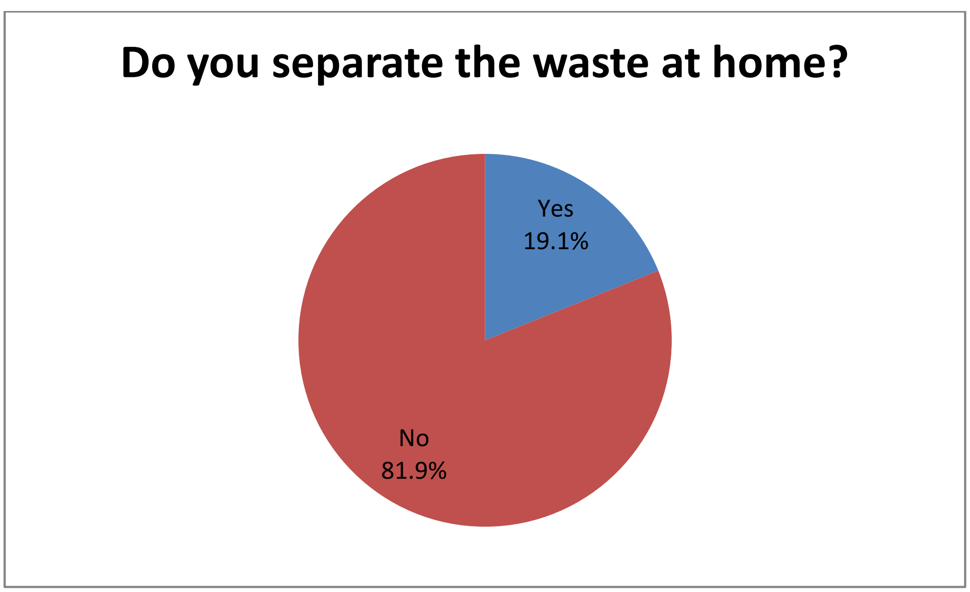
Question 3

Order the following environmental issues according to the risk they represent, in your opinion, to human life							
Answer Options	**1 = Lowest risk**	**2**	**3**	**4**	**5 = Highest Risk**	**Rating Average**	**Response Count**
Water Contamination	7	9	18	52	121	4.31	207
Air Contamination	4	16	37	97	54	3.87	208
Waste Management	5	52	95	41	14	3.03	207
Energy Supply	27	104	51	15	11	2.42	208
Noise	164	27	7	2	8	1.38	208
						answered question	**208**
						skipped question	**10**



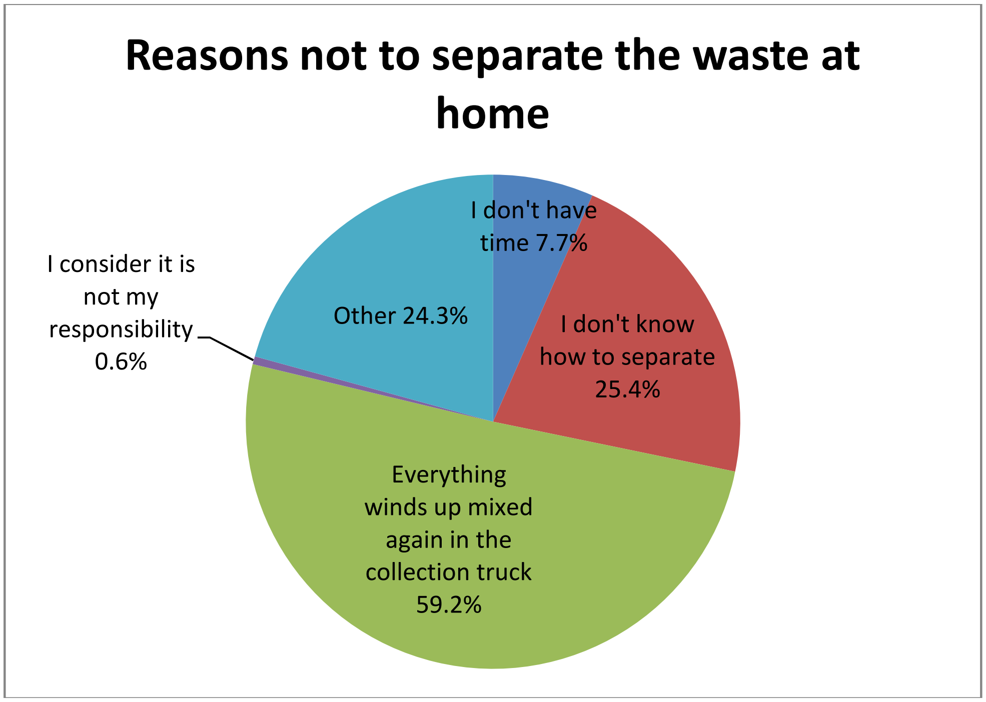
Question 4

Do you separate the waste at home?		
Answer Options	Response Percent	Response Count
Yes	19.1%	39
No	81.9%	167
	answered question	204
	skipped question	14



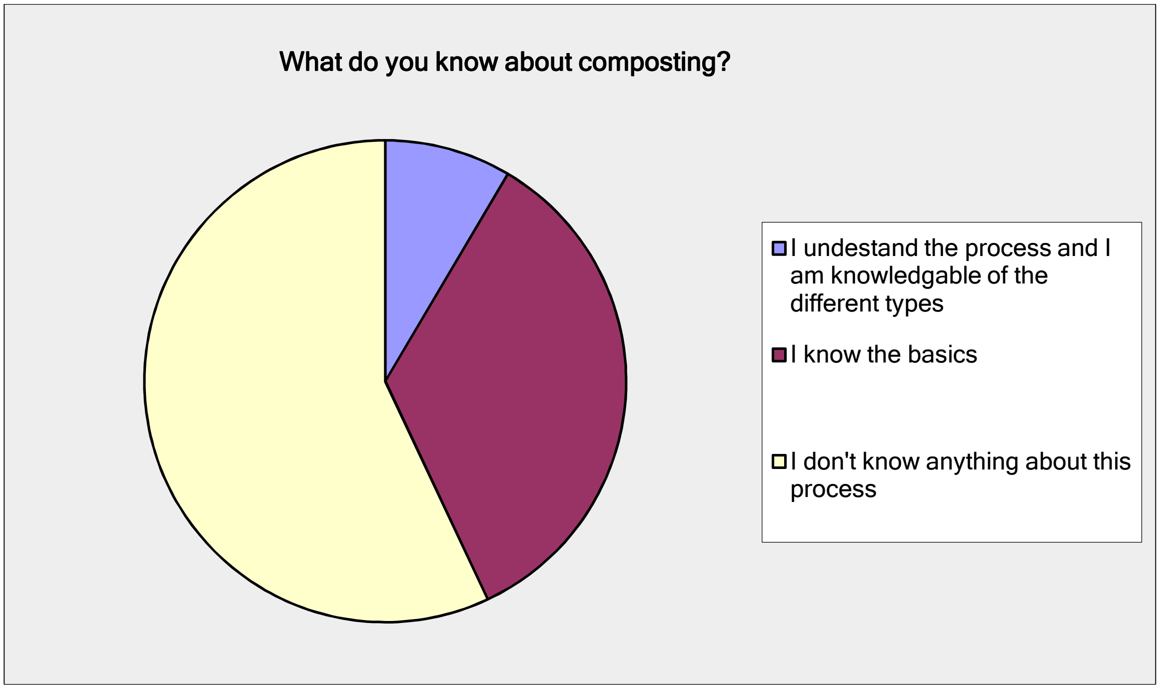
Question 5

If your previous answer was No, what is the reason?		
Answer Options	**Response Percent**	**Response Count**
I don’t have time	7.7%	13
I don’t know how to separate the waste	25.4%	43
Everything winds up mixed again in the collection truck	59.2%	100
I consider it is not my responsibility	0.6%	1
Other:	24.3%	41
	answered question	169
	skipped question	49



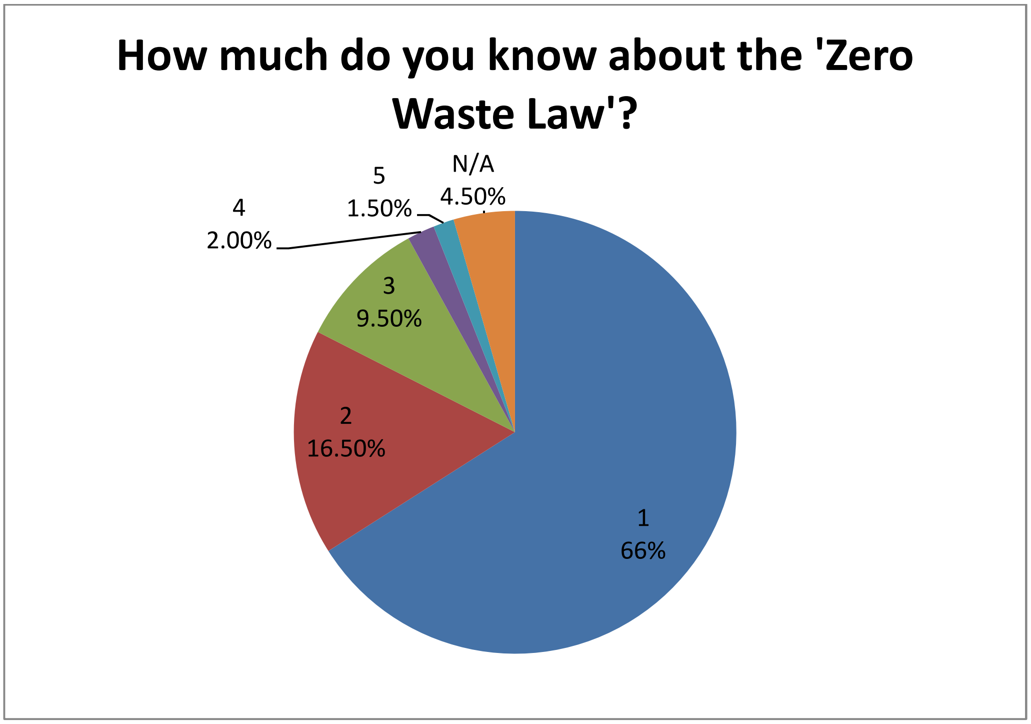
Question 6

What do you know about the composting process?		
Answer Options	**Response Percent**	**Response Count**
I understand the process and I know the different types of composting	8.5%	17
I understand the bascis	34.5%	69
I son’t know anything about the process	57.0%	114
	answered question	200
	skipped question	18

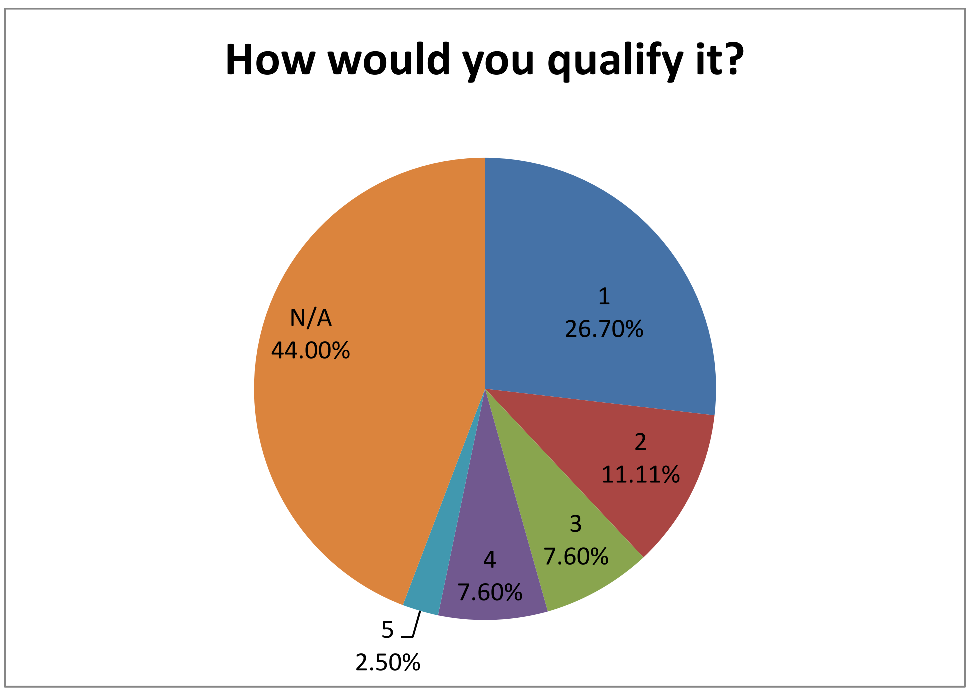


Question 7

Please answer the following questions (1=Very little/ Very poor, 5=A lot/Excellent)								
Answer Options	**1**	**2**	**3**	**4**	**5**	**N/A**	**Rating Average**	**Response Count**
How much do you know about the collection system of residues in your city?	68	57	45	25	3	2	2.18	200
How would you qualify this service?	28	58	71	30	2	11	2.58	200
How much do you know about the 'Zero Waste Law'	132	33	19	4	3	9	1.50	200
How would you qualify it?	53	22	15	15	5	88	2.06	198
If you know, what is the collection frequency? (days, hours)								98
							answered question	200
							skipped question	18

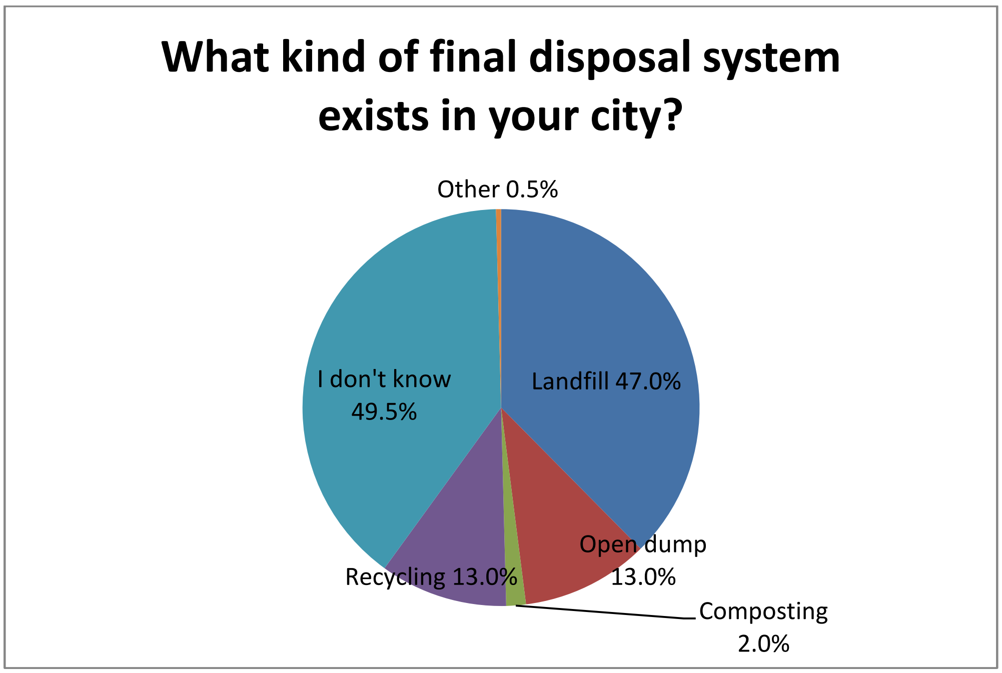


Reference code: 1= Very little/Very Poor; 5: A lot/Excellent



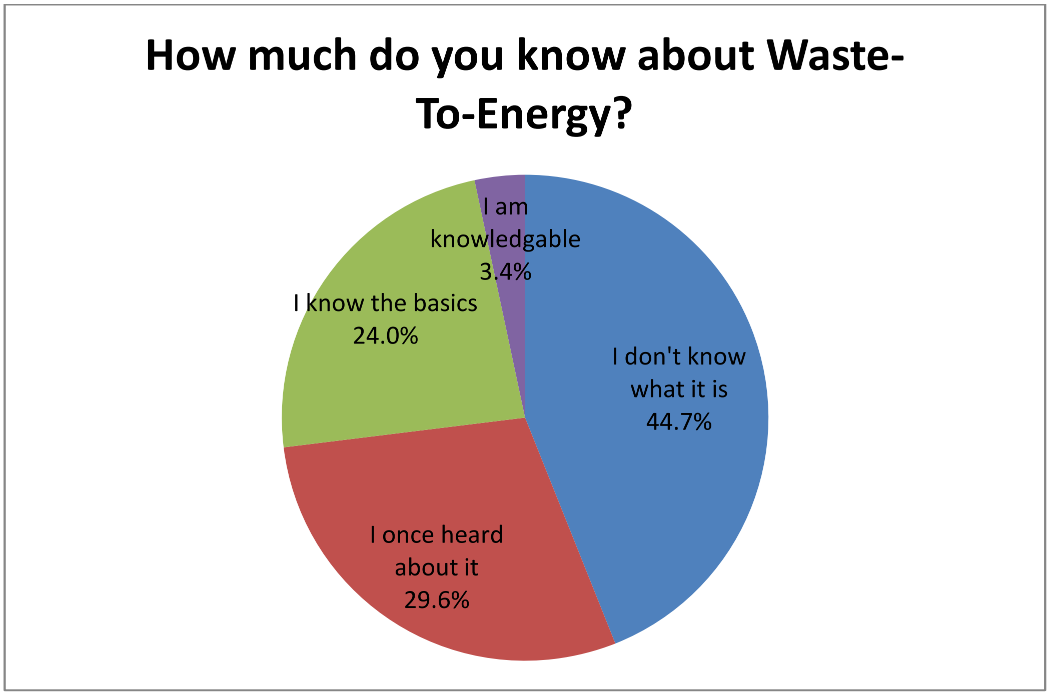
Question 8

What kind of final disposal system exists in your city?		
Answer Options	**Response Percent**	**Response Count**
Landfill	47.0%	94
Open Dump	13.0%	26
Composting	2.0%	4
Reciclynig	13.0%	26
I don’t know	49.5%	99
Other (please specify)	0.5%	1
	answered question	200
	skipped question	18



Question 9

How much do you know about Waste to Energy?		
Answer Options	**Response Percent**	**Response Count**
I don’t know what it is	44.7%	80
I once heard about it	29.6%	53
I know the basics	24.0%	43
I am knowledgeable	3.4%	6
If you know, please explain briefly		24
	answered question	179
	skipped question	39



Question 10

Rank the risk associated to each of the following municipal solid waste treatments							
Answer Options	**1 = Lowest risk**	**2**	**3**	**4**	**5 = Highest risk**	**Rating Average**	**Response Count**
Landfill	15	15	51	52	46	3.55	179
Open dump	4	5	18	31	121	4.45	179
Composting	57	57	51	7	7	2.16	179
Recycling	131	35	9	2	2	1.37	179
Other mechanical or biological treatments	35	81	44	11	8	2.31	179
Incineration	3	17	30	61	68	3.97	179
Waste to Energy	20	48	71	33	7	2.77	179
Comments							29
						answered question	179
						skipped question	39

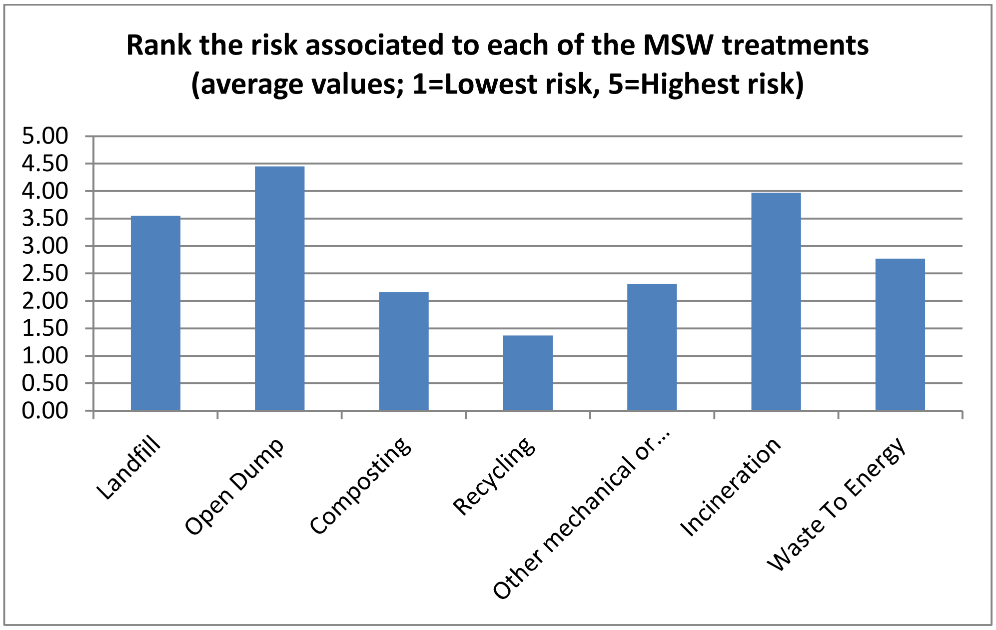

Rank the risk associated to each of the MSW treatments
(average values; 1=Lowest risk, 5=Highest risk)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Landfill
Open Dump
Composting
Recycling
Other mechanical or…
Incineration
Waste To Energy

Exhibit B: Regulated Electricity Fees

Fee 1 (Low demand: maximum demand below 10 kW)

T1 – R residential use

T1- R1 - Bimonthly consumption less or equal to 300 kWh		
Fixed fee (with or without consumption)	$/bim	4.46
Variable charges for energy	$/kWh	0.081

T1- R2 - Bimonthly consumption of 301 kWh to 650kWh		
Fixed fee	$/bim	16.28
Variable charges for energy	$/kWh	0.042

T1- R2 - Bimonthly consumption of 651 kWh to 800kWh		
Fixed fee	$/bim	18.97
Variable Charges for energy	$/kWh	0.045

T1- R2 - Bimonthly consumption of 801 kWh to 900kWh		
Fixed fee	$/bim	20.09
Variable charges for energy	$/kWh	0.047

T1- R2 - Bimonthly consumption of 901 kWh to 1000kWh		
Fixed fee	$/bim	21.59
Variable charges for energy	$/kWh	0.049

T1- R2 - Bimonthly consumption of 1001 kWh to 1200kWh		
Fixed fee	$/bim	24.22
Variable charges for energy	$/kWh	0.100

T1- R2 - Bimonthly consumption of 1201 kWh to 1400kWh		
Fixed fee	$/bim	26.14
Variable charges for energy	$/kWh	0.104

T1- R2 - Bimonthly consumption of 1401 kWh to 2800kWh		
Fixed fee	$/bim	26.14
Variable charges for energy	$/kWh	0.148

T1- R2 - Bimonthly consumption greater than 2800kWh		
Fixed fee	$/bim	26.14
Variable charges for energy	$/kWh	0.238

T1 – G General Use

T1- G1 - Bimonthly consumption less or equal to 1600 kWh		
Fixed fee	$/bim	13.33
Variable charges for energy	$/kWh	0.210
	s	

T1- G2 - Bimonthly consumption greater than 1600 kWh and less or equal to 4000 kWh		
Fixed fee	$/bim	100.46
Variable charges for energy	$/kWh	0.157

T1 - G3 - Bimonthly consumption greater than 4000 kWh		
Fixed fee	$/bim	275.89
Variable charges for enrgy	$/kWh	0.125

T1 – A.P. Public Lighting

Variable charges for energy	$/kWh	0.085

Fee 2 (medium demand: max. average demand > 15 consecutive min. between 10 and 50 kW)

Power charges	$/kW-mes	14.51
Variable charges for energy	$/kWh	0.130

Fee 3 (high demand: max. average demand over 15 consecutive minutes is over 50 kW)

Low Tension		Value (Power < 300 kW)	Value (Power >= 300 kW)
Peak power charges	$/kW-mes	15.43	15.42
Off-peak power charges	$/kW-mes	11.11	11.11
Variable peak charges	$/kWh	0.097	0.132
Other variable charges	$/kWh	0.082	0.116
Valley variable charges	$/kWh	0.073	0.107
Medium Tension		**Value (Power < 300 kW)**	**Value (Power >= 300 kW)**
Peak power charges	$/kW-mes	8.92	8.90
Off-peak power charges	$/kW-mes	6.71	6.71
Variable peak charges	$/kWh	0.093	0.125
Other variable charges	$/kWh	0.078	0.111
Valley variable charges	$/kWh	0.069	0.102
High Tension		**Value (Power < 300 kW)**	**Value (Power >= 300 kW)**
Peak power charges	$/kW-mes	3.92	3.91
Off-peak power charges	$/kW-mes	0.91	0.91
Variable peak charges	$/kWh	0.089	0.120
Other variable charges	$/kWh	0.075	0.106

Valley variable charges	$/kWh	0.066	0.097

Reactive Power Fees

Fee 3		
Additional charge for every centesimal of phi tangent over 0,62 for the excess reactive power of 62%. Applied over the total active energy	%	1.5

Charges for Reactive Power: Fees 1 and 2

For cosene of phi less than 0,85 and up to 0,75	%	10.0
For phi cosene less than 0,75	%	20.0

Quality of the Technical Product Norms

The electricity supply will have to be effective betwee the following admissible tension limits with respect to its nominal value

High Tension	+/-	5.0%
Low and medium air tension grids	+/-	8.0%
Low and medium underground grids	+/-	5.0%
Rural grids	+/-	10.0%

PART B:

Upgrading Low BTU Fuels to Reduce Emissions in Internal Combustion Engines

Executive Summary

Landfills are the most common method utilized to dispose of municipal solid waste in the American Continent. Their emissions of landfill gas, the gas emitted from the anaerobic decomposition of the municipal solid waste, are composed of CO_2 and CH_4. Therefore, this gas has a high global warming potential (CH_4's global warming potential is 21 times that from CO_2). However, the landfill gas also embodies a free source of low BTU fuel.

It is common practice to collect landfill gas and destroy it, mitigating the greenhouse gas emissions associated with it. There are numerous existing technologies to carry this destruction, with different levels of complexity. One of the most commonly used destruction technologies that takes advantage of the energy content of the landfill gas at the same time as the waste's destruction is internal combustion engines. This is the preferred technology because of its cost-benefit ratio. However, these engines produce pollutants as a subproduct of the combustion including NO_x, CO, and UHC (unburned hydrocarbons) emissions. This not only represents a threat to the environment, but in many cases will keep the internal combustion engines from installation because of their resulting inability to comply with stricter regulations that establish low emissions limits of those pollutants.

Previous research at the Combustion and Catalysis Lab (CCL) at Columbia University has shown that by supplementing the input gas stream with as little as 5% Syngas, the emissions of NOx can be reduced up to 40%, CO up to 67%, and UHC up to 80%[1]. The present study analyses the effects of the addition of Syngas to fuel mixes that combust at the same adiabatic temperature to prove that the difference in the emissions are due to the addition of Syngas, and not a result of temperature differences. Experimental work was conducted on a Honda GC 160E with various input gas compositions, registering the exhaust gas composition from the engine.

Results show that an increase in the percentage of Syngas that composes the input gas mix resulted in NO_x emissions reductions for Syngas contents above approximately 15%. Increases of one percentage point of Syngas flow can lead to NO_x emissions reductions of up to 5%. On the other hand, the experimental results for CO and UHC showed that these emissions increased as the percentage of Syngas increased because fluid dynamics governed in the cylinder.

[1] McKenzie P. Kohn, Jechan Lee, Matthew L. Basinger, and Marco J. Castaldi, "Performance of an Internal Combustion Engine Operating on Landfill Gas and the Effect of Syngas Addition" Department of Earth & Environmental Engineering, Henry Krumb School of Mines, Columbia University, Room 926, New York, United States. February 7, 2011.

Table of Contents

1. Introduction

Landfills are currently the most common system used in the American Continent for the final disposal of solid waste. They are projected to retain that status for the forthcoming years. The release of Landfill Gas (LFG), mainly composed of CH_4 and CO_2 in an average ratio of 50%-50%, to the atmosphere constitutes an important environmental issue. The released CH_4 - methane is a Greenhouse Gas (GHG) with a global warming potential 23 times stronger than CO_2. For instance in the US, landfills are the third largest anthropogenic cause of CH_4 emissions representing 17% of the total methane emissions for the country according to the 2009 US EPA statistics.[2] For this reason, LFG is in most cases collected and destroyed. On the other hand, LFG can be a free source of low BTU fuels. One example for the potential use of the collected LFG is as Internal Combustion (IC) engine fuel to generate electricity. However, because of the fluctuations in the composition of the gas, higher emissions of pollutants such as UHC, NOx, and CO are released. Therefore it is important to lower the emissions of these toxic gases whose expulsion is regulated by the EPA.

Based on preliminary studies one solution to this air pollution issue is to add Synthesis Gas (Syngas) -H_2 and CO- to the input LFG in order to reduce the emission of the above stated pollutants. This study will present experimental work and results obtained based on this premise.

2. Landfill gas

LFG is the mix of emissions that come out from landfills as the result of the anaerobic decomposition process by microbes, which breakdown the perishable material therein. Consequently, the composition of the LFG will vary based on (i) the waste composition, (ii) the availability of the substrates to the microorganisms, and (iii) the environmental conditions such as moisture, pH, and temperature.

The waste received by non-hazardous Landfills consists of a variety of municipal solid waste (MSW), industrial wastes, biosolids (sewage sludge) from wastewater treatment, and construction and demolition (C&D) waste. Each country establishes their own management system that will determine whether C&D wastes can be disposed of at the same site as MSW or if they are to be disposed of at a separate landfill. For instance, both the US and Argentina sometimes dispose of C&D waste in specific C&D Landfills and sometimes in general Landfills together with MSW. Since C&D is mostly non-putrescible, the methane content of landfills containing exclusively C&D waste is usually lower (around 30%) compared to a pure MSW landfill.

As LFG is a biologic product, its composition is heterogeneous, and very difficult to predict. The main components are methane (CH_4) and carbon dioxide (CO_2), in an average ratio of 50-50%. In addition, there are smaller amounts of other gases – usually responsible for bad odors when applicable- that can be present in the LFG such as hydrogen sulfide and other sulfur compounds and Non-Methane Organic Compounds (NMOC). Because the CO_2 that is present in the LFG is a result of a natural process it can be

[2] US Environmental Protection Agency, 'Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2009. Executive Summary'. April 2011. Available at http://epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Executive-Summary.pdf

classified as biogenic CO_2, as opposed to the fossil CO_2 which is the result of the combustion of fossil fuels.

The main portion of biodegradable waste is comprised of Cellulose[($C_6H_{10}O_5$)n] and hemicellulose [($C_5H_8O_4$)n] Lignin is also a substantial portion of the organic components. However, this structural component of wood is largely non-degradable under landfill regular conditions. Household waste usually contains 40-50% cellulose, 7-10% hemicelluloses, and 10-20% lignin.

Under anaerobic conditions, the decomposition of cellulose and hemicellulose can be described by Equation) and Equation 1): $(C_5H_8O_4) + H_2O = 2.5CO_2 + 2.5CH_4$

$$(C_6H_{10}O_5) + H_2O = 3CO_2 + 3CH_4$$

Equation 1

$$(C_5H_8O_4) + H_2O = 2.5CO_2 + 2.5CH_4$$

Equation 1

2.1 Landfill gas uses and applications

As presented in Section 2, LFG is primarily composed of CH_4 and CO_2. The well known and commonly used fuel, natural gas, is in actuality mainly composed of CH_4. Therefore LFG when properly utilized can be considered a free fuel. However, since the LFG also contains CO_2, the energy content of the gas is lower and results in LFG's classification as a low BTU fuel.

The release of LFG to the atmosphere is undesirable not only because it is explosive, but also because of its Global Warming Potential (GWP). As alluded to earlier, CH_4 has a GWP 23 times that of CO_2 in a 100-years time horizon. It is common practice to mitigate the consequences of the release of LFG to the atmosphere by burning the CH_4 into CO_2 through flares. By utilizing the flares, the GWP of the CH_4 portion is diminished 23 times, and the gas is no longer explosive. However, this method of limiting the GWP also has a negative component in that the energy content of the CH_4 is wasted. Other alternative methods to the use of flares for the disposal of LFG that benefit from the energy content of the LFG while avoiding its release to the atmosphere are presented as follows.

<u>BTU upgrade:</u> This alternative method converts LFG into a richer fuel such as Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) to use in vehicles. Its advantage resides in the environmental benefits of this fuel compared to gasoline or diesel fuels in producing a significantly cleaner combustion. The gas is purified and dried through separators, filters, carbon activated adsorbents, and zeolites. The separation of the CO_2 through a cryogenic purifier follows, to yield a product composed of 90% to 97% CH_4.

Another alternative method for upgrading the BTU content is the separation of the LFG into two streams to produce pipeline quality high BTU methane and commercial CO_2. The CH_4 stream is cleaned and then fed into existing natural gas distribution networks. The CO_2 is also treated and yields high-purity quality liquid that can be commercialized in the food industry. An example of this practice is observed at the Freshkills landfill in New York, NY.

A third method for upgrading the BTU content is the conversion of LFG to methanol and ethanol, which are used as cleaner fuels than gasoline and can be applied as (i) chemical feedstock, (ii) used in hydrogen production, or (iii) used as transportation fuel or fuel additive.[3]

<u>LFG Direct use:</u>

Direct use of LFG refers to the use of LFG in displacing natural gas (or other fuels) in equipment such as boilers, engines, gas turbines, or fuel cells, and represents a renewable source of energy. Applications in gas turbines and fuel cells are very rarely seen, but the LFG combustion in boilers and, particularly, in engines, are quite common.

LFG can be burned in a boiler for several purposes such as: (i) to displace natural gas and transmit thermal energy, (ii) to be utilized as a source of heating to households and (iii) for industrial applications all year round.

The most common use of the energy content in LFG because of the cost-benefit equation, is to burn it in an internal combustion engine and produce electricity with a generator a process known as LFG to energy. Even though this process mitigates the GHG emissions of the LFG, the counteracting effect is the release of typical combustion byproducts, such as NO_x, CO, and UHC – this reaction is what the experiment presented in this work will focus on.

3. Air Pollution

The air we breathe is considered to be polluted when certain concentration levels of pollutants such as chemicals, biological materials, or particulate matter are reached. Since this thesis pertains to internal combustion engines, pollutants that result out of this combustion are going to be the focus of this section, particularly carbon monoxide (CO), unburned hydrocarbons (UHC), and nitrogen oxides (NOx).

A complete combustion of the fuel, CH4 in this case, would be represented by Equation (2) as follows:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O + Heat$$

Equation (2)

However, when the combustion is incomplete, the carbon from the fuel partially oxidizes into CO, and another portion of the fuel reacts partially, releasing UHC through the exhaust gas.

Carbon Monoxide:

CO is a by-product of an incomplete combustion that occurs when there is not enough oxygen available. The less efficient the combustion is, the more CO is generated (thus less CO_2). CO is a toxic gas for

[3] http://www.climatetechnology.gov/library/2003/tech-options/tech-options-4-1-2.pdf

humans because it combines with the hemoglobin, a compound that provides for oxygen delivery to the bodily tissues, rendering this delivery ineffective. The severity of the symptoms depends on both the CO levels and the exposure time. Exposure to low to moderate concentration levels a of CO result in symptoms such as fatigue, shortness of breath, headaches, nausea, and dizziness. Higher levels of exposure produce additional symptoms including mental confusion, vomiting, loss of muscular coordination, loss of consciousness, and ultimately death.

Unburned hydrocarbons: UHC (or VOCs, Volatile Organic Compounds) are a consequence of the portion of the fuel that was partially burned in the combustion because of inefficiencies of the reaction. They are not toxic by themselves, but they become hazardous when they react with nitrogen oxides in the presence of sunlight to form ozone, a major component of smog. The presence of ozone at a ground level can produce respiratory problems as well as lung damage, eyes irritation, and potentially cancer.

Nitrogen Oxides: NOx refers to both NO and NO_2. These components are the result of the oxidation of the nitrogen that is present in the air, which occurs at high temperatures. As mentioned before, NO_x reacts with VOCs to form smog. Moreover, NO_x also reacts with atmospheric moisture to form nitric acid, a main component of acid rain. These reactions are described in Equation (3), Equation (4), and Equation (5):

$$2NO_2 + H_2O \rightarrow HNO_2 + HNO_3$$

Equation (3)

$$3HNO_2 \rightarrow HNO_3 + 2NO + H_2O$$

Equation (4)

$$4NO + 3O_2 + 2H_2O \rightarrow 4HNO_3$$

Equation (5)

There are four mechanisms that govern NO_x formation: thermal, fuel, nitrous and prompt.

The thermal NO_x - or Zeldovich mechanism - is the most common mechanism of NO_x formation, and is highly dependent on high temperature and the residence time. Equation (6), Equation (7), and Equation (8) are the three primary equations which illustrate this mechanism:

$$N_2 + O \rightarrow NO + N$$

Equation (6)

$$N + O_2 \rightarrow NO + O$$

Equation (7)

$$N + OH \rightarrow NO + H$$

Equation (8)

Fuel NO_x takes place when the reactive fuel contains nitrogen groups. This mechanism is not applicable to the experiments that are being developed in the present thesis since the fuels do not contain nitrogen. An example of a fuel with nitrogen would be coal.

Prompt NO_x is the mechanism that explains the reaction of N_2 that is present in the air with the radicals containing fuel (i.e. C, CH, CH_2) to form cyano-radicals that are oxidized to generate NO. This mechanism usually occurs in the beginning of the combustion, and its contribution is minimal compared to the thermal NO_x.

The nitrous mechanism is pressure dependant. This mechanism can play a role in compression engines where the compression ratio is 8:1 or higher. However, lower pressures do have an impact. The main reaction scheme is shown below, where nitrogen and atomic oxygen combine via a third body collision to stabilize a nitrous molecule. This nitrous molecule can exit the engine or further react to form NO.

$N_2 + O + M \rightarrow N_2O$

$N_2O + O \rightarrow NO + O_2$

4. Experimental Background

The present work uses the same equipment as the previous experiments conducted at the Combustion and Catalysis Lab (CCL) at Columbia University and it should be understood as a continuation of them in search of additional data to better understand the mechanisms that are taking place.

Preliminary data has shown that by supplementing the input gas stream with as little as 5% Syngas, the emissions generated by the engine combustion can be reduced by as much as 40% for NOx, 67% for CO, and 80% for UHC. More detailed data needs to be collected for different Syngas, LFG, and total input gas compositions, which is the purpose of this thesis.

In the past, different proportions and varying compositions of Syngas were added to a 50% CH_4 50% CO_2 gas composition yielding 0.2, 0.4, 0.6, and 0.8 kWh of power.

5. Equipment used

The system used to run the experiments is based on a structure previously constructed at CCL with a series of enhancements incorporated. Figure 1 illustrates the arrangement of the gases and equipment used to carry out the experiments involved in this thesis. The set-up begins with the input gases composed of CH_4 and CO_2. The gases are contained in separate cylinders so that the desired proportion levels can be simulated. H_2 and CO are likewise contained in separate cylinders to simulate the added Syngas. A stream of air is also introduced to the system in order to produce the combustion.

All of the flows are monitored with flow meters, an OMEGA mass-flow meter model FMA1745 (Figure 3) is utilized for the air stream, and a Fisher & Porter Co. rotameter (Figure 2) for each of the other gases. The OMEGA mass flow meter corrects the flow to standard conditions of temperature and pressure of 25°C and 1atm. The mass flow meter's accuracy is ±1.5% of full scale, including linearity over 15 to 25°C and 5 to 60 psia per manufacturer' s specifications. That is, ±15 l/min in this case.

Based upon the rotameters' calibration curves as set forth in Section 7.2 Quality Assurance and Quality Control Proceduresbelow, the rotameter readings were correlated to the flow through the following equations:

Table 1- Calibration curve equations for CH4, CO2, H2 and CO gases

Gas	Calibration equation	R^2	Error [l/min]
CH_4	$y = 1.7503x^2 + 6.4456x$	0.9885	0.49
CO_2	$y = 0.6736x^2 + 5.6277x$	0.9943	0.38
H_2	$y = 3.0287x^2 + 18.258x$	0.997	1.28
CO	$y = 0.4257x^2 + 9.5817x$	0.998	0.60

The last column of **Error! Reference source not found.** indicates the error of each rotameter expressed in a flow unit of liters per minute. This error corresponds to the minimum unit of measurement in the instrument, utilizing the calibration equations to convert it to flow.

The mixing chamber (Figure 4) is the spot where all of the gases are mixed together. The chamber was designed with a diameter wider than the tubing so that the gases would expand thereby lowering their pressure, and allowing the mix despite the different pressures of the input gases.

The next piece of equipment is the Honda GC 160E-QHA engine (Figure 5), which can be classified as an internal combustion and spark engine. This engine had previously gone through a series of modifications in order to be able to (i) operate with gaseous fuel, (ii) allow the operator to control the air ratio, and (iii) introduce a gas analyzer that would measure the gas composition of the exhaust gas in a reliable way – for details on these modifications see Mr. Jechan Lee's M.S. thesis. The engine operates with an 8.5 compression ratio. Figure 5 provided herein includes an image of the engine model used, and **Error! Reference source not found.** provides a summary of the manufacturer's specification data.

Attached to the engine is the PRAMAC EG2800 generator (Figure 6), which is connected to a load board (Figure 7) composed of bulb lights that allows the variation of the electrical load of the engine by turning on and off the desired amount of bulb lights. This load board consists of 16 bulb lights (eight 100 watt lights and eight 200 watt lights) connected in parallel. The lights are paired such that they share a switch every two lights. Therefore, if an engine load of 0.2 kW is desired, the switch corresponding to a pair of 100-watt bulbs is turned on. If the desired load is 0.4 kW, two switches corresponding to two pairs of 100-watt bulbs are turned on, and so on.

As regards the generated power, this data is also monitored through two multimeters (Figure 8), one that is connected in parallel to measure voltage and one that is connected in series to measure current. The voltage and current data are then multiplied to calculate the power.

The engine exhaust gas composition is monitored with a portable emission gas analyzer instrument, ENERAC 700 (Figure 9). This device has a small pump inside which pulls a sample of the gas that is being analyzed. The water content of the gas is eliminated by a thermoelectric cooler, which means that all of the data is measured on a dry basis. Finally, the gas is analyzed by a number of SEM electrochemical, electrochemical, and three-channel NDIR (Non-Dispersive InfraRed) gas sensors, which includes sensors for Carbon Monoxide, Carbon Dioxide, Hydrocarbons, Nitric Oxide, Nitrogen Dioxide, Sulfur Dioxide, and Oxygen. **Error! Reference source not found.** shows the type of sensor for each of the gases, and the accuracy and resolution associated therewith.

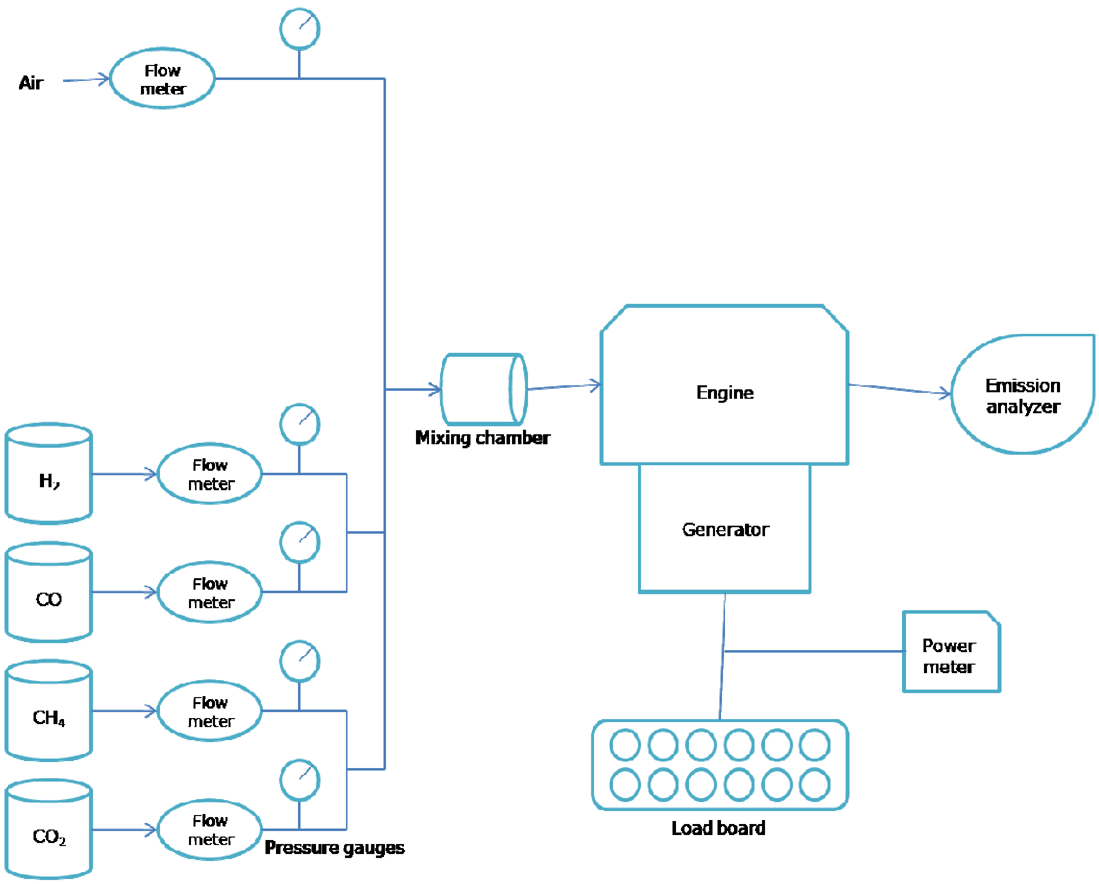


Figure 1 - Experimental system circuit

Figure 2 - Fisher & Porter Co. Rotameters

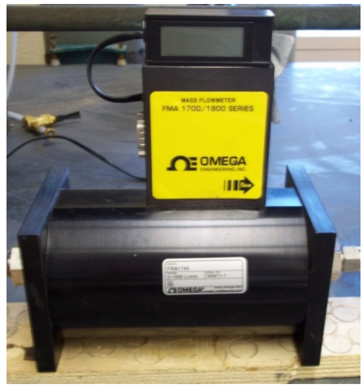


Figure 3 - Omega FMA 1745 mass flow meter

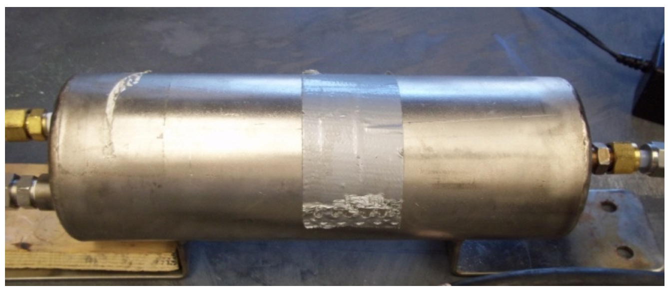


Figure 4 - Mixing chamber

Figure 5 - Picture of Honda GC 160E - QHA engine

Table 2- Specification of the Honda Engine used

Length × Width × Height	13.3 × 14.5 × 13.0 in. (337 × 369 × 331 mm)
Dry weight	25.4 lbs (11.5 kg)
Engine type	4-stroke, overhead cam, single cylinder
Displacement [Bore × Stroke]	9.8 cu-in. (160 cm^3) [2.5 × 2.0 in. (64 × 50 mm)]
Max. output	4.9 bhp (3.7 kW, 5.0 PS) at 3600 rpm
Max. torque	7.6 lbf ft (10.3 N m, 1.05 kg m) at 2500 rpm
Fuel tank capacity	0.53 US gal (2.0 L)
Fuel consumption	0.51 lb/hph (313 g/kWh, 230 g/PSh)
Cooling system	Forced air
Ignition system	Transistorized magneto
PTO shaft rotation	Counterclockwise
Spark plug gap	0.028 – 0.031 in. (0.70 – 0.80 mm)
Valve clearance (cold)	IN: 0.15 ± 0.04 mm EX: 0.20 ± 0.04 mm

Figure 6 – Pramac EG2800 generator

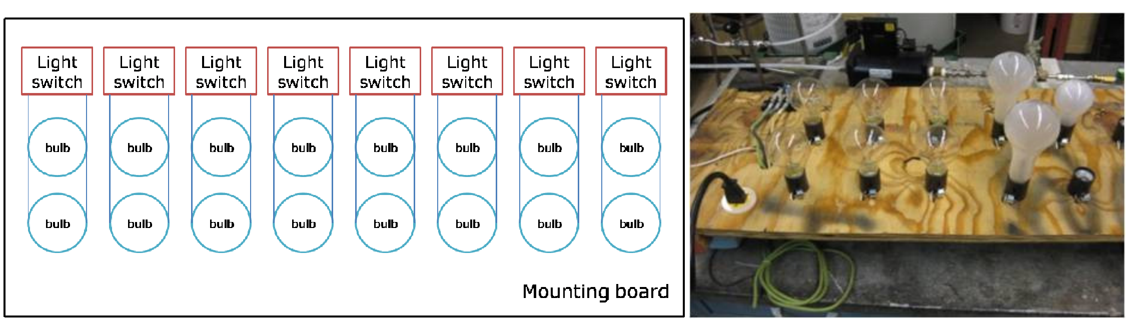


Figure 7 - Left, scheme of the connections of the bulb lights that constitute the power load board. Right, photo of the power board

Figure 8 - Multimeters used to measure voltage and current

Figure 9 - Emission gas analyzer ENRAC 700

Table 3 - Classification of the sensors present in ENERAC 700

Gas	Type of sensor	Range	Resolution	Accuracy
Carbon Monoxide	SEM electrochemical sensor	0-2000 ppm	1 ppm	2 ppm or 2% of reading
Carbon Monoxide	Infrared (NDIR) technology	0.00-10.00% 10.00% -15.00%	0.01%	0.02% or 3% read. 5% of reading
Carbon Dioxide	Infrared (NDIR) technology	0.00-16.00% 16.00%-20.00%	0.01%	0.3% or 3% read. 5% of reading
Hydrocarbons	Infrared (NDIR) technology	0-2000 ppm 2001-15000 ppm 15001-3000 ppm	1 ppm	4 ppm or 3% 5% of reading 8% of reading
Nitric Oxide	SEM electrochemical sensor	0-300 ppm 2000/4000 ppm	0.1 ppm 1 ppm	2 ppm or 2% of reading 5 ppm or 5% of reading
Nitrogen Dioxide	SEM electrochemical sensor	0-300 ppm 1000 ppm	0.1 ppm 1 ppm	2 ppm or 2% of reading 5 ppm or 5% of reading
Sulfur Dioxide	SEM electrochemical sensor	0-2000 ppm 6000 ppm	0.1 ppm 1 ppm	2 ppm or 2% of reading 5 ppm or 5% of reading
Oxygen	Electrochemical	0.0-25.0%	0.1%	0.1% absolute or 0.2% of reading

6. Purpose

The purpose of this experiment is to show that both the amounts of CO and UHC are reduced because the input of Syngas to the fuel increases fuel's activity due to its higher flame speed and the NO_x formation is mitigated as a consequence of a more stable combustion at lower temperatures. More detailed data needs to be collected for different Syngas, LFG, and total input gas compositions.

All the tests are run in a Honda Engine GC160 with Maximum Power output of 2kW. However, the emission levels of 4 different engines with bigger capacity-Capstone CR200, Solar Centaur 40, Caterpillar G3516 LE-have also been compared. It was observed that the results of the experiments can be extrapolated to an industrial scale as well.

This research is an application of a larger study currently conducted by the CCL at Columbia University, on the development of a dry-reforming catalytic reactor. Dry-reforming is the reaction of LFG that produces Syngas, as Equation 9 shows:

$$CH_4 + CO_2 \rightarrow 2\,H_2 + 2\,CO \qquad \Delta H = 247\,\frac{kJ}{mol}$$

Equation 9 - Dry reforming

The concept consists of pulling a portion of the LFG that would go straight to the engine and passing it through the catalytic reactor in order to generate Syngas. This Syngas would then be mixed back with the LFG and the mix would be combusted in the engine Therefore, this study concentrates on the effects of the mix of the Syngas that would be produced by the reactor with LFG on the engine emissions. Figure 10 below illustrates the mechanism.

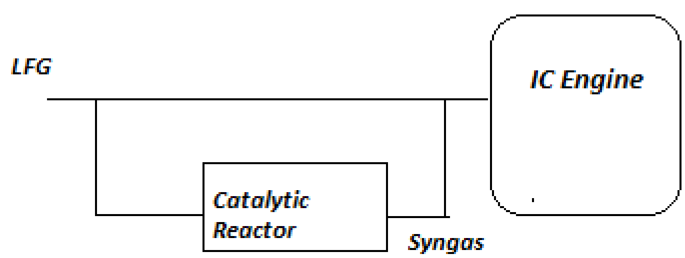


Figure 10 - Catalytic reactor and engine system

7. Experimental Work

7.1 System modifications

This section sets forth the series of enhancements that were introduced to the existing system in order to conduct the experiment.

Flow Meters: The rotameters that monitor the flow of CH_4, CO_2, H_2, and CO were attached to wood to form a board that would simplify the reading of the flow when logging the values for each gas, thereby reducing the potential for human error in the readings. In addition, the rotameter that was installed in the air stream was replaced with a digital OMEGA mass flow meter that fits better with the flow scale utilized in the experiment. The rotameter used in the previous experiments operated at an optimum range that was higher than the flow to be operated in for this experiment. This optimum range issue in the previous experiments was therefore a source of potential error in the measurements. Therefore, the instrument was replaced with the digital mass-flowmeter to provide more reliable values.

Tubing, parts and accessories: Additional pieces of tubing were incorporated as needed in the system. All the parts and accessories in the arrangement were checked. As a result, the valves that were found to fail were replaced for alternative pieces that were properly operating.

Power Meter: The generated power was previously measured with a Wattsup power meter. This instrument has a limited operative range, which represented a limitation on the combinations of experimental sets. Moreover, the power meter was proven to be read with a significant drift. Consequently, the device was replaced by two multimeters to measure voltage and current, so that the values would be multiplied to obtain the power. This new monitoring system leaves the experiment free of restrictions as far as power metering concerns, and provides more reliable data since the digital mass flow meters have a higher precision level compared to the rotameter.

Engine stabilization: When modifying the engine for the purpose of adapting it to the experimental structure, the muffler was extracted. As a result, the engine operates with significant noise and vibrations. Since these vibrations were affecting the accuracy of the exhaust gas analysis by destabilizing the probe attached to the emission gas analyzer and often pushing it out, a heavy wood was attached to the bottom of the engine to provide it with additional stability.

Instrument repairs: Both the ENERAC 700 gas analyzer and the OMEGA mass flow meter were found to be non-functional for different reasons at the initial stage of the equipment set-up – the readings of the mass flow meter were always on the negative range and the gas analyzer was unable to be turned on. Therefore, both pieces of equipment had to be sent for repairs to the corresponding manufacturer. The malfunctioning of the OMEGA mass flow meter was determined to be just a calibration issue and the instrument was consequently factory calibrated. On the other hand, the repairs necessary for the ENERAC gas analyzer were more complex. The manufacturer repaired the instrument and also performed maintenance on its the sensors as per their recommendations. These maintenance and repair operations assisted in ensuring a reliable set of data logged from the experiment performed.

7.2 Quality Assurance and Quality Control Procedures

In addition to the enhancements introduced to the experimental set up developed in section 7.1 which improved the reliability level of the readings, calibrations on each monitoring instrument were performed at least twice during the period when the experiment was developed.

The rotameters were calibrated with a bubble meter. A bubble meter is a glass tube with volume marks that has a rubber piece attached that allows the generation of a soap bubble on the bottom of the tube.

A gas flow is allowed to enter the tube, moving the soap bubble throughout the tube. Finally, the gas flow can be calculated by measuring the time the bubble takes to travel through a known volume. The rotameter calibration depends on the gas that is being used, the temperature and the head pressure at which the gas is fed. Therefore, the same rotameter was always used for the same gas stream, and the selected head pressure of calibration was set at 25 psi. The experiment was exposed to ambient temperature, which we assumed remained constant. The fluctuations, if any, in the ambient temperature could result in very small variations in the data and therefore it is deemed reasonable to neglect them. Figure 11, Figure 12, Figure 13, and Figure 14 show the calibration curves generated for the different rotameters.

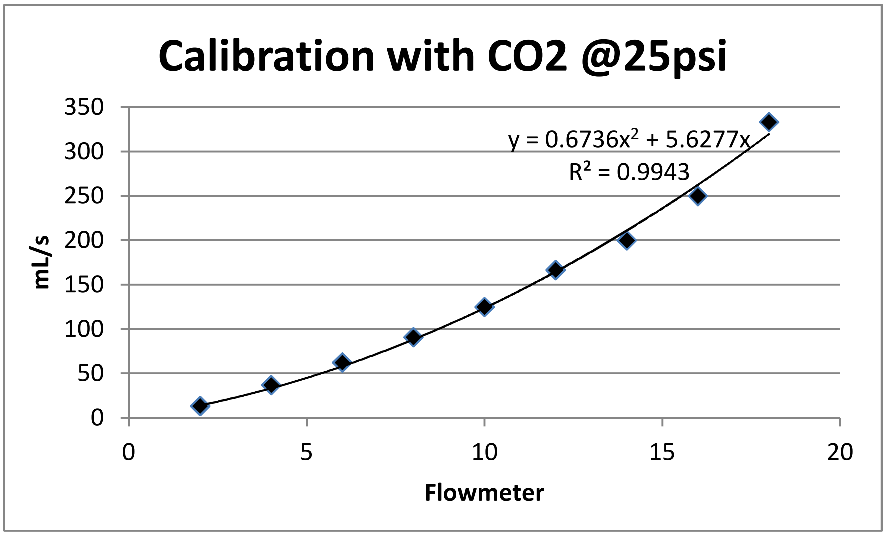


Figure 11 - CO_2 Calibration curve. Head pressure = 25 psi

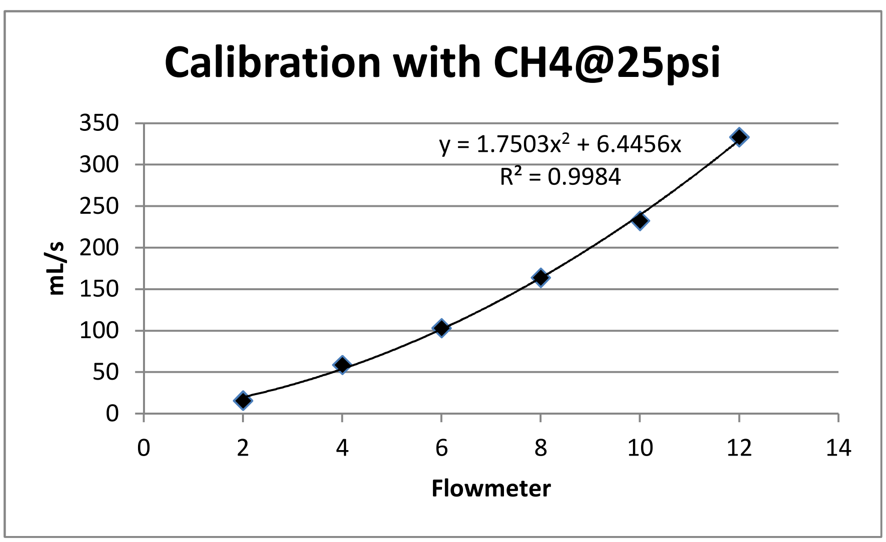


Figure 12 - CH_4 Calibration curve. Head pressure = 25 psi

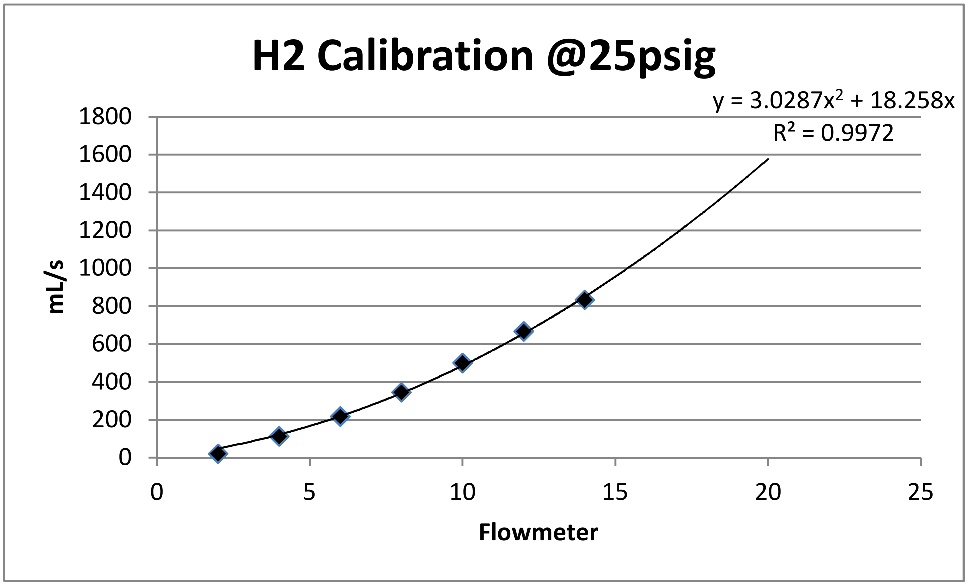


Figure 13 - H2 Calibration curve. Head pressure = 25 psi

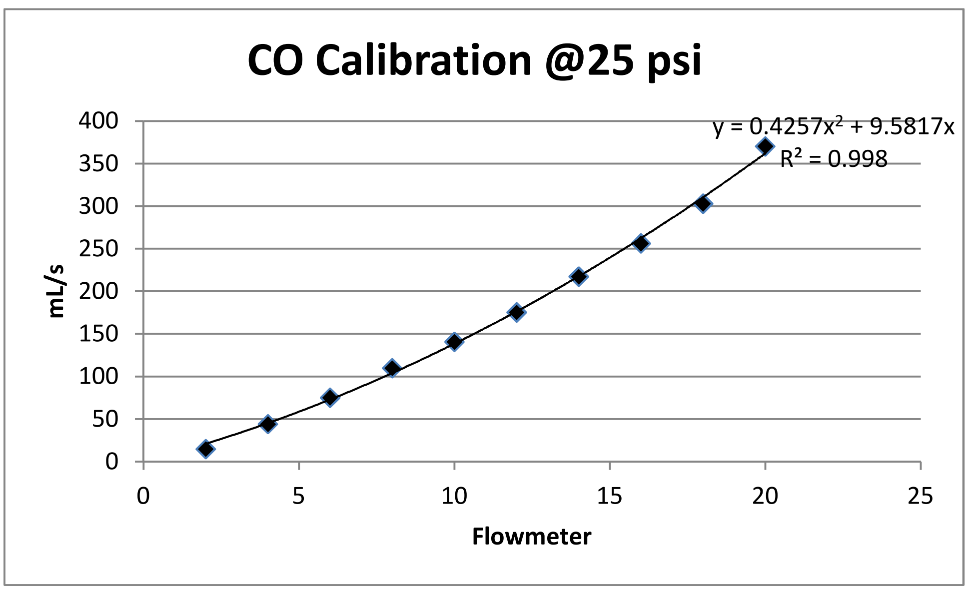


Figure 14 - CO Calibration curve. Head pressure = 25 psi

The mass flow meter required a different type of calibration. This instrument has a multipin outlet that provides voltage readings that vary linearly with the flow. The voltage readings range is 0 – 5 volts, handling flow rates of 0 – 1000 l/min. A digital output reader was attached to the instrument, and these readings were calibrated through the voltage output of a series of flows, considering the linear characteristics confirmed by the manufacturer – note that the instrument was factory calibrated right before performing the experiments as mentioned in Section 7.1. Because this mass flow meter measures molecular gas flow rate based on heat transfer through a heated tube, the gas mass flow rate is measured directly, without the need to compensate for variations in gas temperature or pressure (within stated limits). Since the experiments were performed under ambient temperature and pressure, it can be assumed that the changes in temperature and pressure do not affect the meter's output. Figure 15 below provides the calibration line with its corresponding equation which was obtained experimentally.

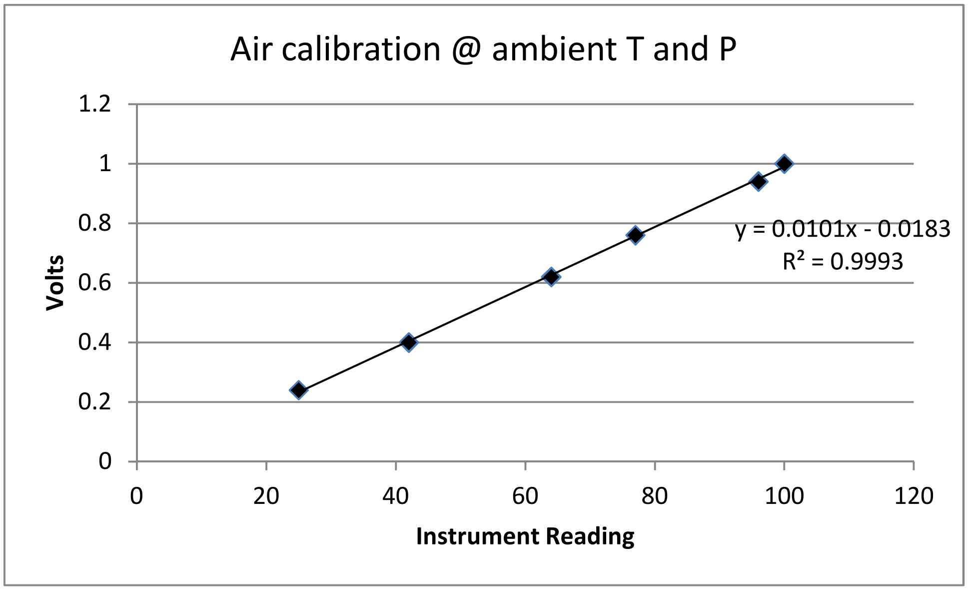


Figure 15 - Calibration curve for air with mass flow meter at ambient temperature and pressure

As regards the ENERAC gas analyzer, the instrument was calibrated on a monthly basis utilizing separated calibration gases for each sensor as per the manufacturer's recommendations. Since the calibration of this instrument is somewhat complex, a calibration checklist was used to ensure that the correct calibration process was followed each time.

The multi-meters were tested to zero; moreover, one of them was brand new. Therefore a calibration to these instruments was not deemed necessary.

7.3 Experimental Procedure

In order to operate the experiments with a set of gas flow combinations that would have a constant adiabatic temperature, an excel spreadsheet was developed to log in the experimental data. This spreadsheet had formulas set to calculate the heat capacity of the input gas, as Equation 10 shows:

$$C_{p,\ ig} = \frac{n_{air} \times 29.07\ \frac{J}{mol.K} + n_{CH4} \times 35.06 \frac{J}{mol.K} + n_{CO2} \times 37.20 \frac{J}{mol.K} + n_{H2} \times 28.87 \frac{J}{mol.K} + n_{CO} \times 29.07 \frac{J}{mol.K}}{n_{air} + n_{CH4} + n_{CO2} + n_{H2} + n_{CO}}$$

Equation 10 - Heat capacity of the input gas calculation, assuming ideal gas behavior[4]

Where

[4] The heat capacity values for air, CH_4, CO_2, H_2, and CO were sourced from Stephen R. Turns, 'An Introduction to Combustion. Concepts and Applications' Second Edition, Appendix A, McGraw-Hill International Editions Mechanical Engineering Series. August, 1993.

$C_{p, ig}$ = Heat capacity of the input gas, in $\frac{J}{mol.K}$

n_{air} = air molar flow, in mol/min

n_{CH4} =methane molar flow , in mol/min

n_{CO2} = carbon dioxide molar flow, in mol/min

n_{H2} = hydrogen molar flow, in mol/min

n_{CO} = carbon monoxide molar flow, in mol/min

The input gas combinations that shared the same Cp when fed into the engine with the same power load were expected to result in similar adiabatic temperatures when combusted. The above concept formed the basis for how the experimental combination of input gases was selected. The following is a detailed description of the procedure followed when running the experiments:

1. All monitoring instruments are turned on: the mass flow meter, the gas analyzer and both multimeters.
    a. In the case of the gas analyzer, the instrument is turned on in a clear environment since the device takes a sample of the air as soon as it is turned on to reference the readings to that defined 'zero'.
2. All valves are collocated in open position except for the ones installed on the streams of the gases that are not used during the start-up (that is, CO_2, H_2, and CO), including the one immediately before the engine.
3. The methane cylinder on-off valve is turned to the on position, and the needle valve is regulated in order to feed the methane with 25 psi, consistently with the head pressure at which the rotameter was previously calibrated. The rotameter is set to feed a very low flow to allow the start-up of the engine.
4. The air stream from the building supply is turned on and regulated to set a very low flow delivery as well to allow the start up of the engine.
5. The engine is turned on using the start-up cord.
6. The valve adjacent to the engine is carefully closed so that all the air coming into the engine is pulled from the building outlet and travelling across the mass flow meter.
7. The bulb-lights from the board are turned on according to the desired power load on the engine.
8. The gas flows of CH_4 and air are modified to the preferred extent for the experimental trial.
9. If any additional gases are desired to be included (or excluded) in the trial, the corresponding cylinder's on-off valves are turned on (or off), the needle valves are set to feed a head pressure of 25 psi -consistently with the head pressure at which the rotameters were calibrated - and the rotameter is adjusted to feed the chosen gas flow amount.
10. Once the selected input gas composition for running the trial is achieved, the engine is left in operation for about five minutes in order to let the ENERAC gas analyzer stabilize.
11. The input gas flows, the exhaust gas composition, the current, and the voltage are logged into a spreadsheet

12. A new combination of input gas flows is chosen and this procedure is repeated as from step 7.

8. Data Analysis and experimental results

Once the experimental data was collected, the data analysis commenced. The first step was to calculate the adiabatic temperature of each run so that these temperatures could be compared and confirmation obtained that the sets that had the same adiabatic temperature. The adiabatic temperature is the temperature at which the reactants and the products of a combustion chemical reaction have the same enthalpy. Therefore, Equation 11 though Equation 15 shows the calculations performed to determine the adiabatic temperature for each trial run:

$$H_{reac}\,(T_i, P) = H_{prod}\,(T_{ad}, P)$$

Equation 11

Where

$H_{reac}\,(T_i, P)$= Enthalpy of the reactants at initial temperature (T_i) and pressure (P), assumed to be 298K and 8.5atm (the engine operates with a 1:8.5 compression ration) for these experiments.

$H_{prod}\,(T_{ad}, P)$= Enthalpy of the products, at adiabatic temperature (T_{ad}) and pressure (P), where P is 8.5 atm as the reactants pressure, since the combustion occurs when the gas is compressed in the engine. The adiabatic temperature is the unknown variable that is being calculated.

Moreover,

$$H_{react} = \sum_{react} N_i \times \bar{h}_i = \sum_{react} N_i \times \bar{h}^{\circ}_{f,i}$$

Equation 12

Where

N_i = molar flow of the reactant i

$\bar{h}_i$= enthalpy of the reactant i, on a molar basis

$\bar{h}^{\circ}_{f,i}$=formation enthalpy of the reactant I, on a molar basis

Note that the reactants temperature (298K) is the same as the reference temperature (298K) and therefore the enthalpy of the reactants equals the formation enthalpy.

And

$$H_{prod} = \sum_{prod} N_i \times \bar{h}_i = \sum_{prod} N_i \times \left[\bar{h}^{\circ}_{f,i} + \bar{c}_{p,i} \times (T_{ad} - 298K)\right]$$

Equation 13

Where

N_i = molar flow of the product i

$\bar{h}_i$= enthalpy of the product i, on a molar basis

$\bar{h}^{\circ}_{f,i}$=formation enthalpy of the product i, on a molar basis

$\bar{c}_{p,i}$= heat capacity of the product i, on a molar basis

T_{ad}= adiabatic temperature, in K

298K = reference temperature

Note that the reactants temperature (298K) is the same as the reference temperature (298K) and therefore the enthalpy of the reactants equals the formation enthalpy.

Combining Equation 11, Equation 12, and Equation 13

$$\sum_{react} N_i \times \bar{h}^{\circ}_{f,i} = \sum_{prod} N_i \times \left[\bar{h}^{\circ}_{f,i} + \bar{c}_{p,i} \times (T_{ad} - 298)\right]$$

Equation 14

And solving for T_{ad}

$$\boxed{T_{ad} = \frac{\sum_{react} N_i \times \bar{h}^{\circ}_{f,i} - \sum_{prod} N_i \times \bar{h}^{\circ}_{f,i} + \sum_{prod} \bar{C}_{p,i} \times 298K}{\sum_{prod} \bar{C}_{p,i}}}$$

Equation 15

Even though the combustion that takes place in the engine is not adiabatic since there is heat loss, i.e. the engine heats up considerably when operating, we can assume that for reactions with the same adiabatic temperature the heat loss in the engine is somewhat constant and therefore the reaction temperature of all of that set of reactions can be assumed to be the same. Given that what we are looking to demonstrate is that the emission reductions are independent from the reaction temperature and, instead, they are caused by the variation in the input gas composition, an approach based on constant adiabatic temperature is suitable for the purposes of this analysis.

The experimental data collected is shown in Table 2 below. The data is organized in groups (A, B, C, etc.) formed by runs (1, 2, 3, etc.) that share the same adiabatic temperature. Each run has a different input gas composition resulting in different associated emissions.

Error! Reference source not found., **Error! Reference source not found.**, and **Error! Reference source not found.** show the variation of CO, UHC, and NOx emissions respectively, for different input gas compositions grouped by adiabatic temperature. The graphs clearly show the adiabatic temperature that corresponds to each group is maintained relatively constant among the runs that integrate the group.

	Input Gas in mol/min						Emissions from ENERAC (mass fraction)						
Group	N2	O2	CH4	CO2	H2	CO	CO2	O2	CO ppm	UHC ppm	NOx [ppm]	Tad	Run #
	2.0691	0.55001	5.7096	5.4573	1.3996	1.8472	1.40%	18.10%	2000	40	58.2	1794.1	1
	2.0691	0.55001	5.7096	5.4573	1.9901	1.8472	1.30%	18.40%	3500	47	57.6	1787.5	2
A	2.0691	0.55001	5.7096	5.4573	3.357	1.8472	1.20%	18.40%	5400	60	31.1	1797.1	3
	2.0691	0.55001	5.7096	5.8688	0	0.8539	11.40%	9.40%	5320	50	358	1924.9	4
B	2.0691	0.55001	5.7096	5.8688	1.9901	0.6274	10.50%	9.10%	12200	80	918	1926.1	5
	2.0691	0.55001	5.7096	5.8688	1.3996	0.6274	11.30%	8.70%	9000	70	1081	1936.3	6
	2.0691	0.55001	5.7096	5.8688	3.357	0.8539	9.70%	9.10%	24700	80	479	1935.6	7
	2.0691	0.55001	5.7096	5.8688	0	0.8539	11.80%	9.10%	5320	50	429	1933.3	8
	2.0691	0.55001	5.7096	5.8688	1.9901	0.6274	11.00%	8.50%	15500	80	1000	1937.5	9
C	2.0691	0.55001	5.7096	5.8688	3.357	0.6274	9.90%	8.60%	22500	70	852	1938.1	10
	2.0691	0.55001	5.7096	5.5385	2.6426	0	9.70%	9.00%	13500	53	611	1916.2	11
	2.0691	0.55001	5.7096	5.8688	0	0.6274	11.40%	9.30%	5240	60	357	1911.7	12
D	2.0691	0.55001	5.7096	5.8688	3.357	0.6274	9.60%	9.40%	23000	90	505	1913.8	13
	2.9743	0.79064	7.4577	7.186	0	0	11.70%	8.50%	4940	30	20	1945.5	14
	2.0691	0.55001	5.7096	5.8688	1.9901	0.8539	10.70%	9.00%	12600	60	812	1944.4	15
E	2.0691	0.55001	5.7096	5.8688	3.357	0.8539	9.70%	8.70%	26700	80	570	1944.0	16
	2.0691	0.55001	5.7096	5.8688	1.9901	0	11.80%	8.50%	6000	70	1069	1906.5	17
	2.0691	0.55001	5.7096	5.8688	3.357	0	9.90%	8.30%	23100	100	917	1900.1	18
F	2.0691	0.55001	5.7096	5.8688	0	0.6274	11.20%	9.50%	5370	50	370	1905.6	19
	2.0691	0.55001	5.7096	5.8688	0	1.3331	11.90%	9.20%	5280	50	440	1963.3	20
G	2.0691	0.55001	5.7096	5.8688	3.357	1.3331	9.80%	9.00%	27700	90	359	1964.8	21
	2.0691	0.55001	5.7096	4.9044	0	0.6274	10.90%	10.00%	5320	50	190	1973.8	22
	2.0691	0.55001	5.7096	5.8688	1.9901	1.3331	10.80%	9.00%	13600	60	614	1975.2	23
H	2.0691	0.55001	5.7096	5.8688	0	1.3331	12.20%	8.90%	5330	40	459	1972.1	24
	2.0691	0.55001	5.7096	5.8688	0	1.8472	12.30%	9.00%	3700	50	617	2004.7	25
	2.0691	0.55001	5.7096	5.8688	1.3996	1.8472	11.40%	8.80%	15500	80	677	2003.6	26
	2.0691	0.55001	5.7096	5.8688	3.357	1.8472	9.90%	8.40%	32200	70	134	2007.4	27
I	2.0691	0.55001	5.7096	5.8688	1.9901	1.8472	11.20%	8.60%	22300	70	90	2005.0	28
	2.0691	0.55001	5.7096	4.9044	3.357	1.3331	9.90%	8.80%	25000	60	483	2061.1	29
J	2.0691	0.55001	5.7096	4.9044	2.6426	1.3331	10.60%	8.70%	19700	50	646	2065.1	30

Table 2 - Experimental results for the different runs, showing input gas composition, exhaust gas composition, and adiabatic temperature

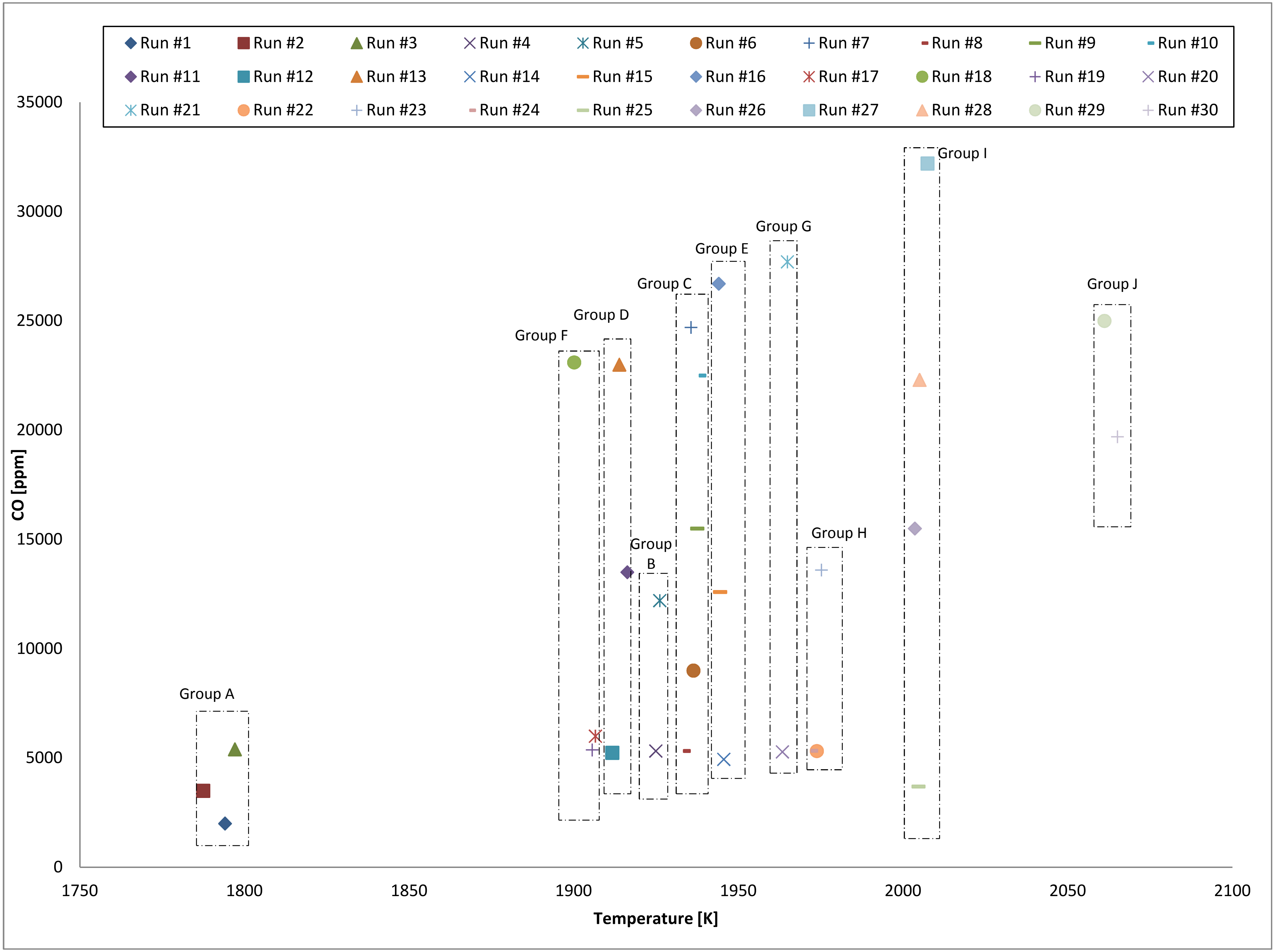


Figure 16 - Variation of CO emissions for different input gas compositions, at constant adiabatic temperature

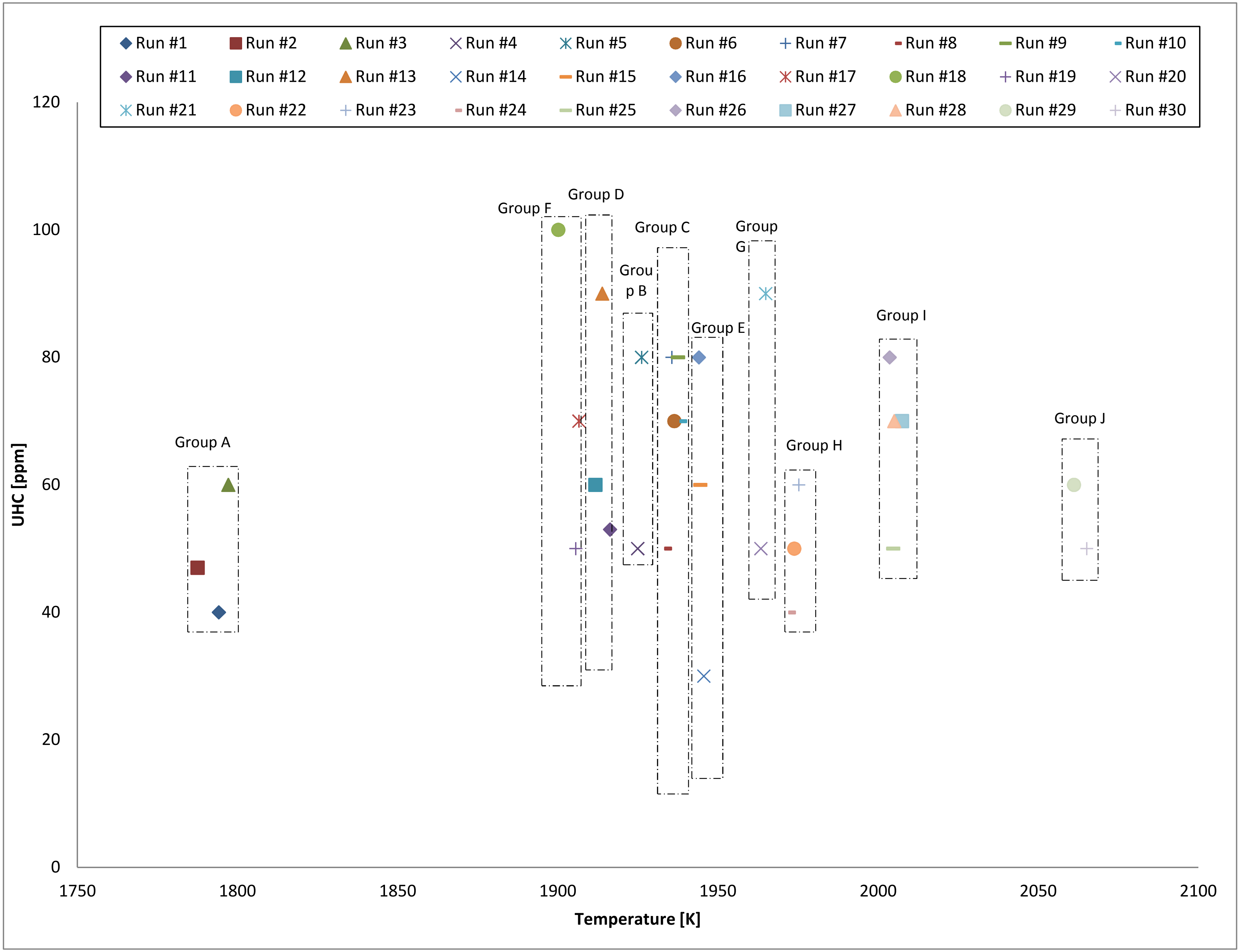


Figure 17 - Variation of UHC emissions for different input gas compositions, at constant adiabatic temperature

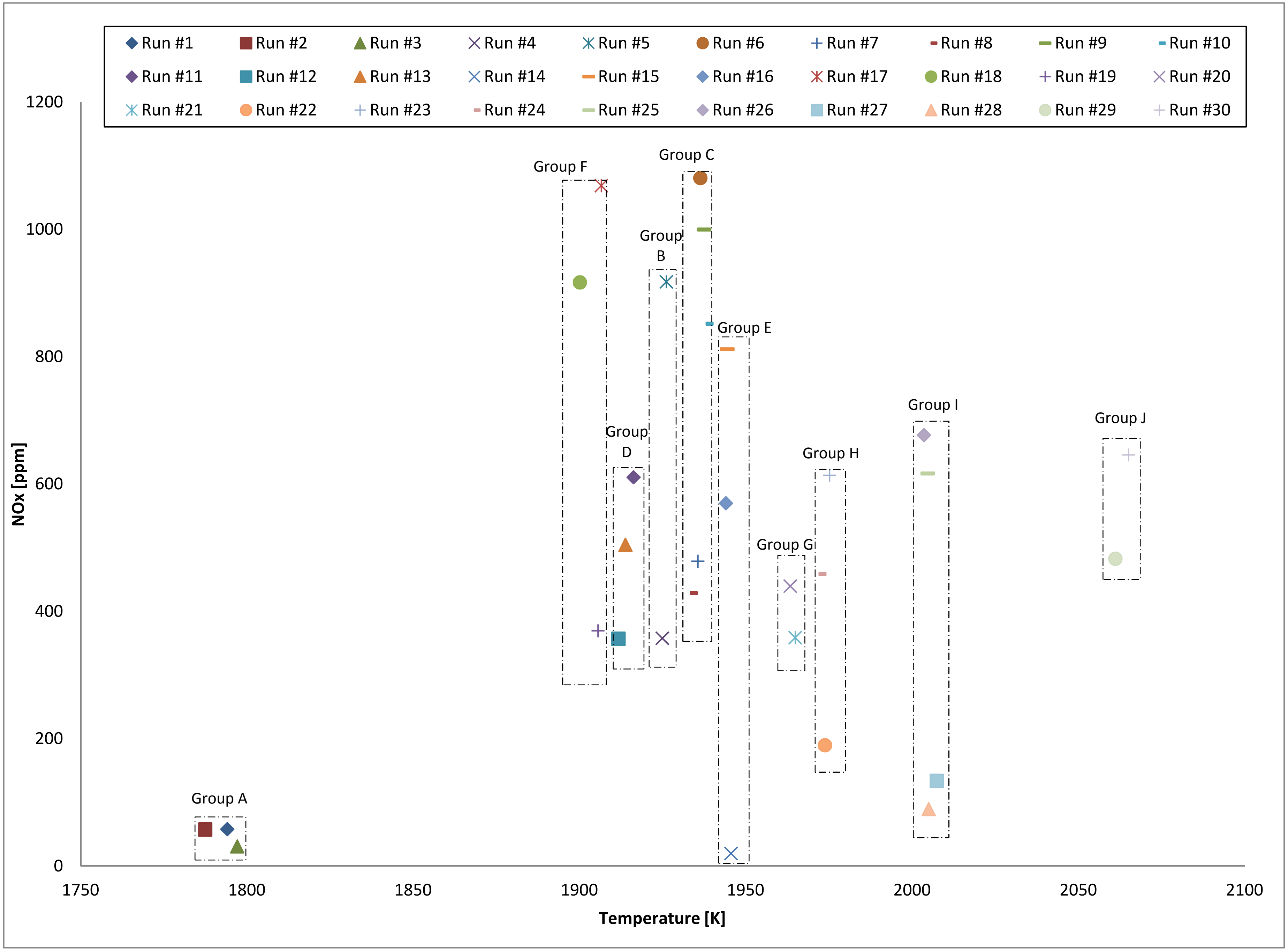


Figure 18 - Variation of NOx emissions for different input gas compositions, at constant adiabatic temperature

8.1 Effects of the addition of Syngas

We begin the study of these experimental results by analyzing the effects of the addition of Syngas into the input gas stream. Because the goal is to analyze the effect solely of the input gas composition in the emissions, the analysis is conducted by comparing runs belonging to the same group to guarantee that the observed changes in the emissions are independent from the temperature of reaction. Moreover, only runs with same input gas flows of air, CO_2 and methane within the group were selected for this analysis, i.e. groups A, B, C, F, G, I, J and D, E, H partially. Therefore, the only variable is the Syngas percentages in the input gas, and the respective H_2/CO ratio of the Syngas.

Figure 19 shows the emissions of CO for the different groups. The emissions of UHC and NO_x for the same groups and runs are shown in Figures 20 and 21, respectively. The green curves group the runs which show an increasing emissions trend with higher Syngas content. Conversely, the blue curves group the runs that show a decreasing emissions trend with higher Syngas content.

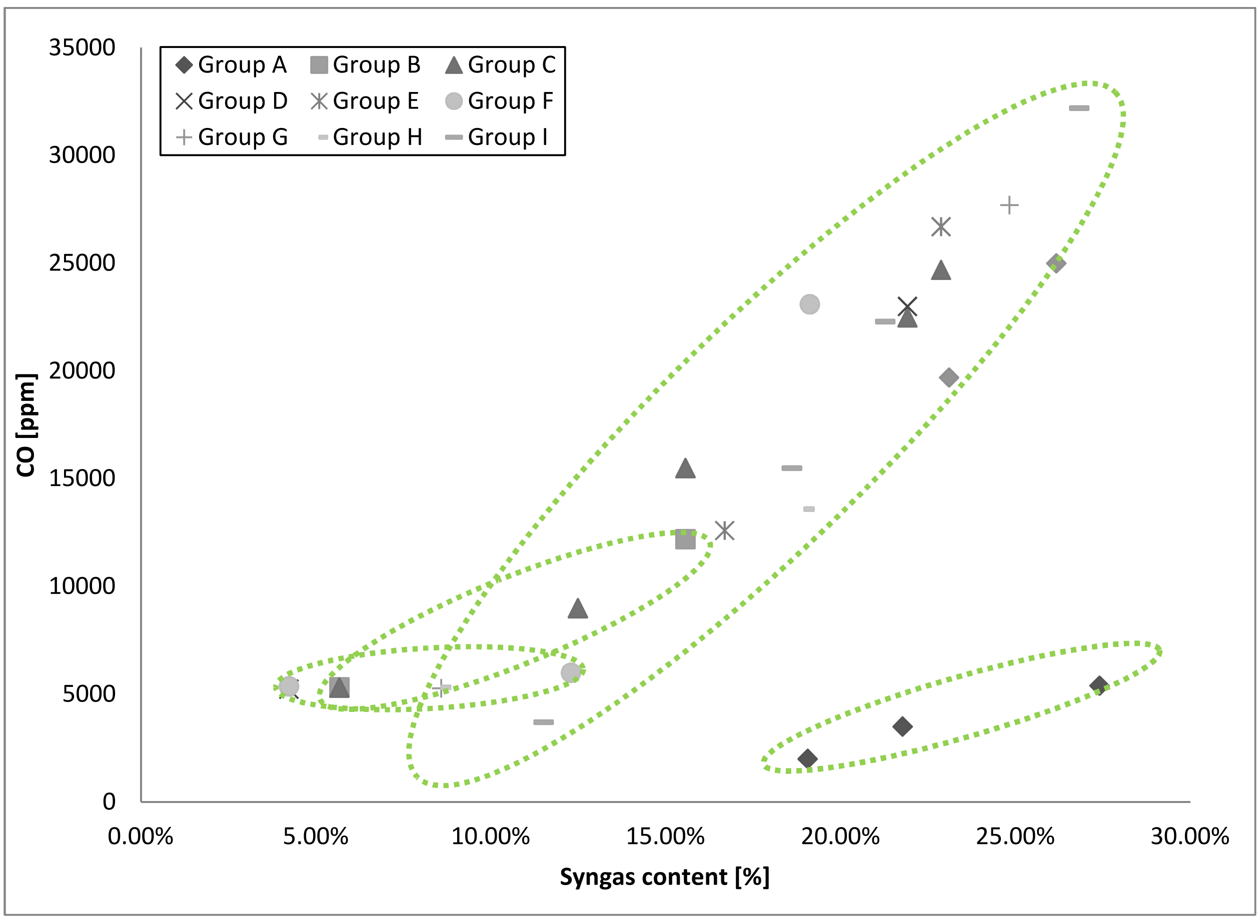


Figure 19 – Experimental results of CO emission concentration versus Syngas content in the input gas

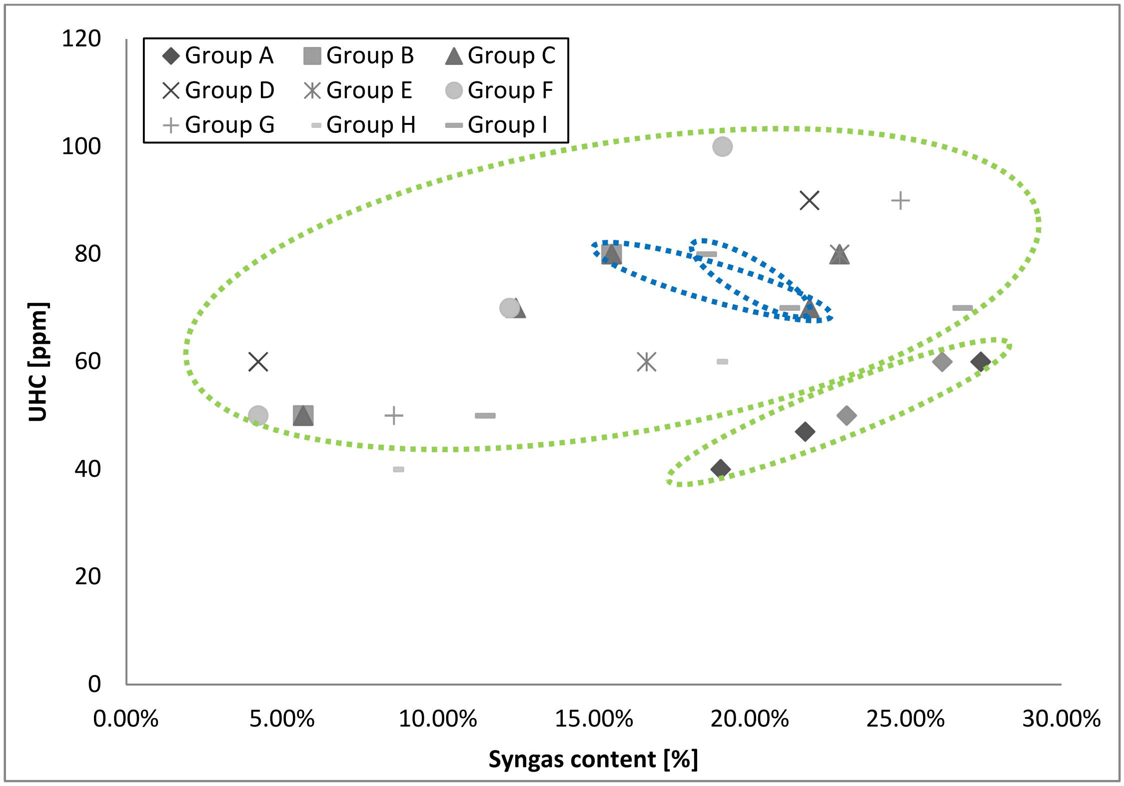


Figure 20 - Experimental results of UHC emission concentration versus Syngas content in the input gas

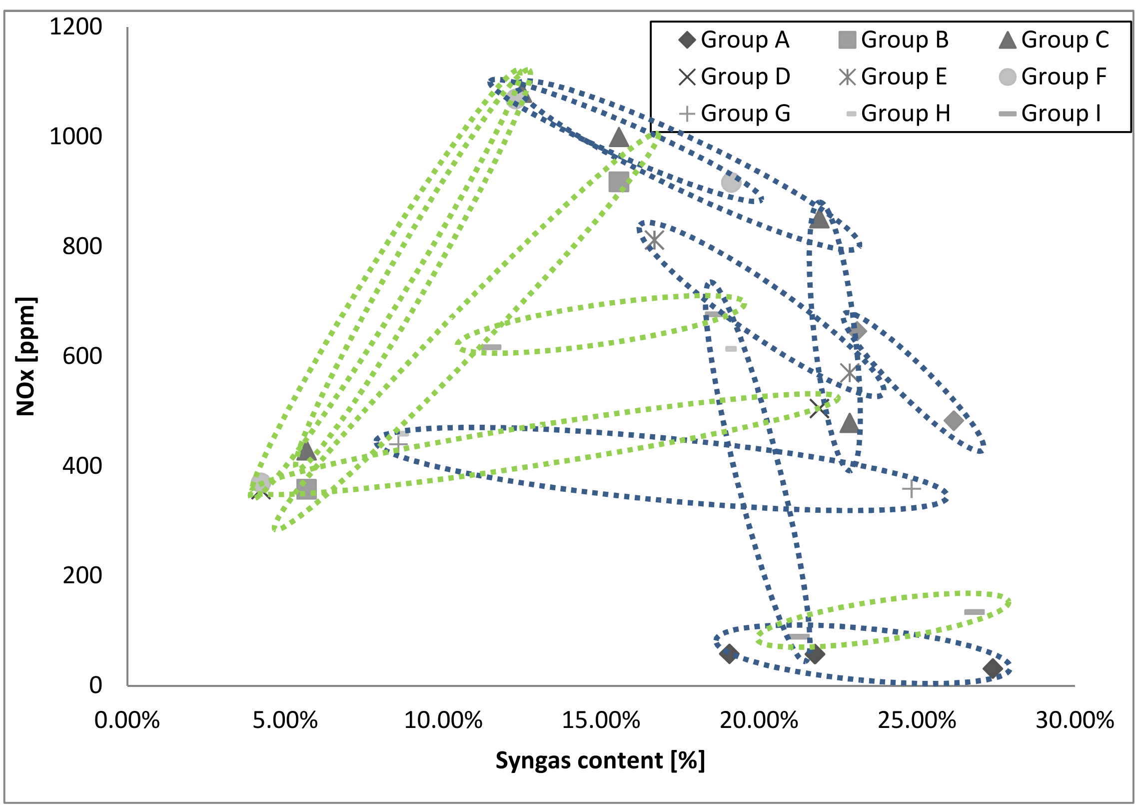


Figure 21 - Experimental results of NOx emission concentration versus Syngas content in the input gas

As a result of the combustible properties that characterize H_2 and CO, it is expected that the combustion of the input gas with some Syngas content will render the input gas into a more reactive fuel and therefore engender lower CO, UHC and NO_x emissions. H_2 has extremely high laminar flame speed, extremely high flammability limits and low dissociation energy, which translates into low ignition energy. Additionally, CO is a highly ignitable gas with very fast burning rate.[5] Figure 19 shows that for all runs, CO emissions increased with Syngas content. Previous studies have shown that only runs with a Syngas component lower than 5% yielded emissions reductions, possibly because at higher Syngas contents fluid dynamics within the cylinder govern the emissions production. Since none of the groups have more than one run with Syngas content less than 5%, the data gathered is consistent with previous studies results. Moreover, Kintecus, a software that calculates the mechanism of a reaction, was used to simulate the same reactions involved in the experiments with the specified input gas composition and adiabatic temperature. It is important to note that because i) the exhaust gas composition varies significantly with time and (ii) the engine is not an adiabatic system, the reactions actually occurred at a lower temperature than the adiabatic temperature and therefore, the Kintecus results are not expected to match at an absolute value. However, the theoretical emission tendencies should correspond to the experimental values.

Figure 22 shows the CO emissions output data from Kintecus. The graph generally shows a slight decrease of about 0.5% of CO emissions per percentage point of added Syngas. This is consistent with the interpretation presented above, which provides that lower emissions result due to the higher reactivity of the input gas. On some occasions, for instance Group C, CO emissions remained constant despite the increase in Syngas content. These observations were engendered by the addition of CO in the input gas that composes the Syngas. The theoretical data is discrepant with the experimental results. Consequently, it is expected that the fluid dynamics were governing in the cylinder, unchanging the results from previous studies. To confirm the latter, a calculation of the experimental kinetic rate of the CO, utilizing run #9 as an example, will be performed. This kinetic rate will be compared to the fluid dynamic rate afterwards.

$$\frac{d[CO]}{dt} = \frac{CO_{in} - CO_{out}}{\tau}$$

Equation 16

Where

$\frac{d[CO]}{dt}$= Rate of reaction of CO

CO_{in} = Amount of CO in the input gas

CO_{out} = Amount of CO in the exhaust

τ = Residence time in the cylinder, calculated as the total cylinders volume over the total input gas flow.

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[5] Dong, C., Zhou, Q., Zhao, Q., Zhang, Y., Xu, T., Hui, S. *"Experimental study on the laminar flame speed of hydrogen/carbon monoxide/air mixtures."* Fuel 88 pp.1858-1863. 2009

The calculated rate of reaction of CO for run #9 is 0.00062 $\frac{mol}{cm^3 x\ min}$. However, the calculated fluid dynamic rate of the total input gas in the system is 0.026 $\frac{mol}{cm^3 x\ min}$ – this rate was calculated as the total gas flow over the volume of the engine cylinders. Therefore, the fluid dynamics are clearly governing in the system.

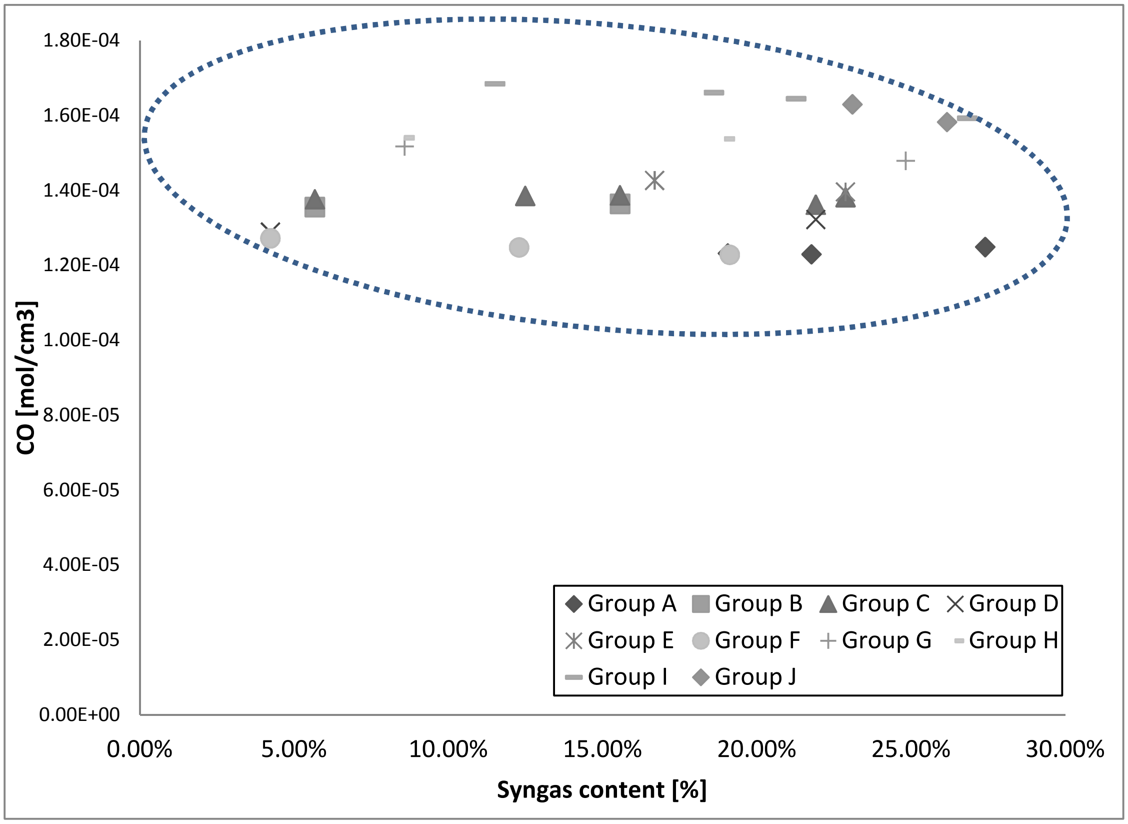

Figure 22 - Kintecus results of CO emission concentration versus Syngas content in the input gas

Similarly to CO, Figure 20 shows an increase of UHC emissions with higher Syngas content. However, runs 9 and 10 from group C and runs 26 and 28 from group I present exceptions. The emissions results were compared to Kintecus results, presented in Figure 23. Again, a generally slight decrease of about 0.7% of UHC emissions per percentage point of added Syngas was expected. Consequently, the UHC emissions trend may be considered the same as the CO emissions trend because the use of Syngas increases the reactivity of the input gas. However, because the fluid dynamics govern in the cylinder, an increase of UHC emissions is observed instead of the opposing trend. Again, we perform the calculations with the experimental data from sample run #9 to support the latter conclusion. Solely for the purpose of these calculations, it was assumed that UHC corresponds only to CH_4. The rate of reaction for UHC is 0.009 $\frac{mol}{cm^3 x\ min}$. Comparing this rate to the previously calculated fluid dynamic rate of 0.026 $\frac{mol}{cm^3 x\ min}$ it can be concluded that the fluid dynamics govern in the system.

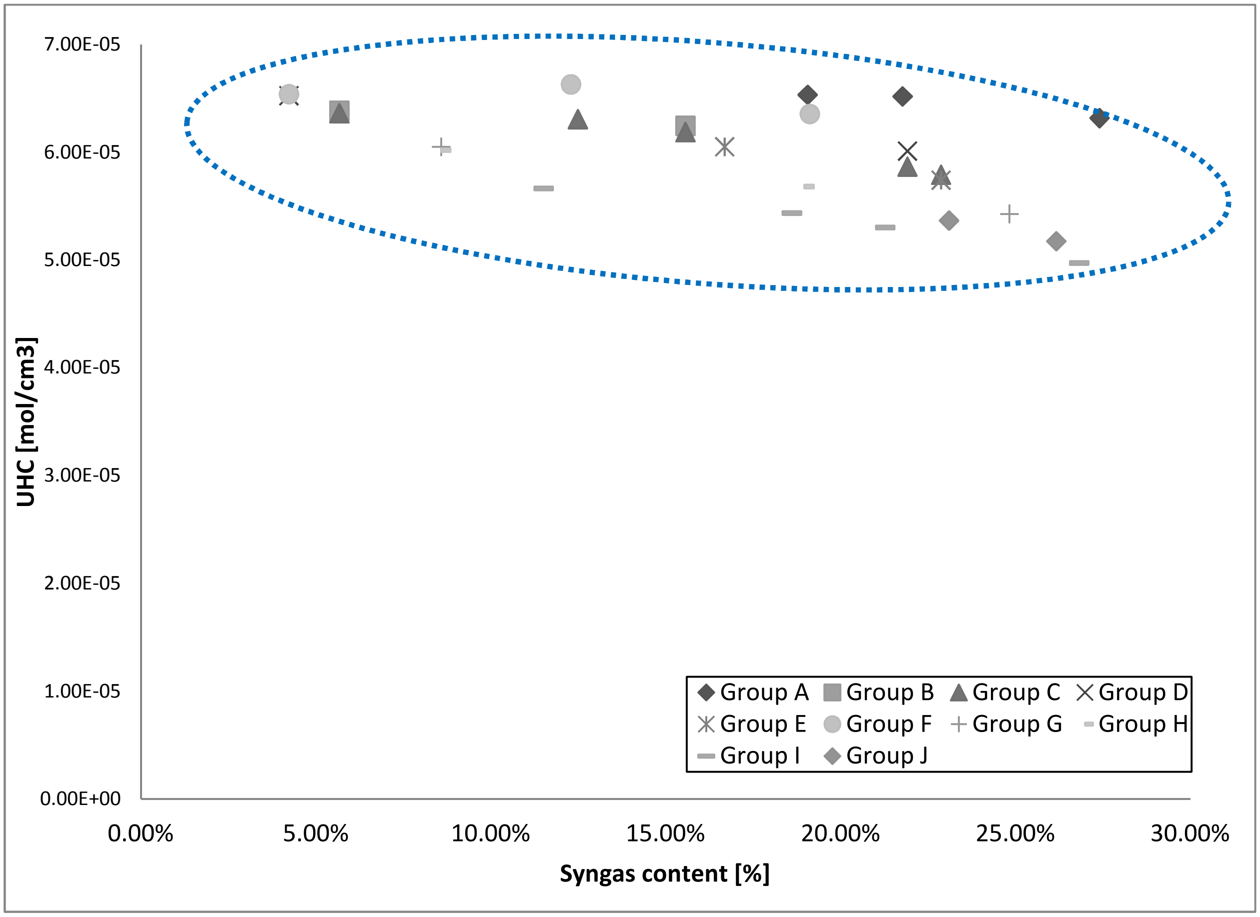

Figure 23 - Kintecus results of UHC emission concentration versus Syngas content in the input gas

When analyzing the effects of the Syngas percentage on the NO_x emissions (Figure 21), inverse tendencies were observed. As usual, Kintecus was utilized to compare the results. Figure 24 shows the NO_x emissions variation with Syngas content in the input gas, based on Kintecus data.

Kintecus results show for all groups, a decreasing output of NO_x emissions when the Syngas percentage is increased. Given that the experimental results show an opposing trend for input gases with low Syngas content, in the range of 5 to 10 percent approximately, it is believed that the fluid dynamics in the cylinder are governing. For higher Syngas contents, the fluids are more likely to be mixed and therefore the expected emissions results matching the Kintecus output are observed, i.e. groups J and E in Figure 21 match entirely the Kintecus result trends even at a similar declining rate of emissions. As mentioned previously, a reduction in the NO_x content of the exhaust gas was expected due to the higher reactivity of the components of the Syngas which would theoretically allow for a more stable combustion of the fuel. However, the fluid dynamics in the cylinder could interfere as well, inducing opposing trends in the emissions.

The increase of a percentage point of Syngas content in the input gas generated almost a 5% decrease of NO_x emissions. The variation of NO_x can assuredly be attributed to the alteration in the Syngas content of the input gas given that all of the other conditions of the reaction remained constant and that each group reacted at the same adiabatic temperature. As observed in Kintecus, the CO and UHC pollutants are formed at a significantly faster speed than NO_x, being less sensitive to Syngas variations than the latter. Further research regarding the mechanisms of the reaction and fluid dynamics of the gas flows in the experimental system is needed to better understand the opposing trends of the different emissions observed experimentally

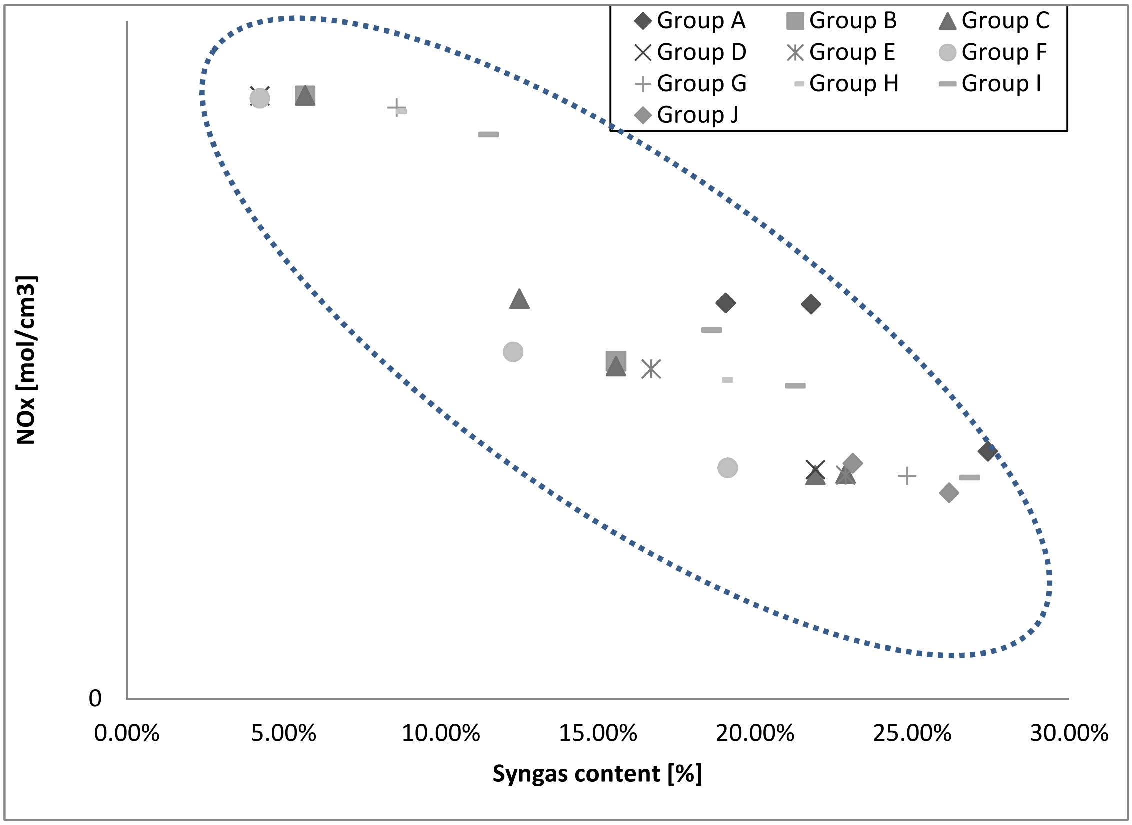

Figure 24 - Kintecus results of NOx emission concentration versus Syngas content in the input gas

10. Conclusions

Various fuel compositions made of landfill gas and Syngas were added to run a Honda GC 160E engine. The trial runs were grouped according to their adiabatic temperature, which was calculated based on the input gas enthalpy and the exhaust gas enthalpy. The emissions in the exhaust gas were compared between the runs with the same adiabatic temperature in order to ensure that the effects on the emissions were independent from the temperature and purely dependent on the input gas composition.

The effects of increasing the Syngas flow when all of the other input gas flows remain constant resulted in higher CO and UHC emissions, but lower NO_x emissions for high Syngas contents (Syngas contents approximately over 15%). The increase of CO emissions with higher Syngas proportions in the input gas occurred at an approximately constant rate, increasing the CO emissions 0.26% per percentage point of Syngas added. The UHC emissions showed a similar behavior when Syngas was incorporated into the reactants, although it only increased at a rate of 0.05% per percentage point of Syngas added. NO_x, however, showed increased emissions for Syngas contents in the range of approximately 5 to 10 percent, but decreased emissions for higher Syngas compositions; 5% per additional percentage point of Syngas. These experimental results depicted discrepancies with the theoretical expected emissions forecasted by Kintecus due to a more stable combustion caused by the higher reactivity that characterizes Syngas compared to the other reactive gases that composed the input fluid. The explanation for the discrepancies between the experimental and the theoretical results is that the fluid dynamics govern in the cylinder. In particular for NO_x, Kintecus results showed that these emissions always decrease at a rate of 5% per additional percentage point of Syngas added to the reactants. Consequently, the fluid dynamics in the cylinder are expected to govern when Syngas content is approximately between 10 and 15 percent. Because the speed of formation of CO and UHC is significantly higher than the rate for NO_x, these pollutants are not as sensitive to Syngas content as the latter. This difference in formation speed explains why the experimental NO_x data was consistent with Kintecus at higher Syngas concentrations, as the fluid dynamics no longer governs, whereas the CO and UHC data was not consistent.

Additionally, no evidence was found that the H_2 to CO ratio of the added Syngas has any effect on the results, and no assertive conclusions as to the effects of this ratio in the emissions can be determined from the presented experimental set of data. Further research needs to be conducted to determine these effects.