

# Landfill gas study performance on a IC Engine with addition of Syngas

**Liubov Melnikova**

Advisor: Prof. Marco J. Castaldi

Co Advisor: Prof. Nickolas J. Themelis

Department of Earth and Environmental Engineering  
Fu Foundation School of Engineering & Applied Science  
Columbia University

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## EXECUTIVE SUMMARY

In this research, Chapter 1 is dedicated to analytical evaluation of landfill gas recovery. The majority of the world's municipal solid waste is still going to the landfills, US being no exception. According to BioCycle and Earth Engineering Center, about 270 million tons of waste are landfilled annually in US. Anaerobic degradation, a naturally occurring process on the landfills, generates landfill gas which mainly consists of methane and carbon dioxide. Methane is a highly potent greenhouse gas that can be captured and used in a variety of applications. When methane from the landfill is collected and used it not only prevents the gas from escaping into the atmosphere, but also displaces the Carbon Dioxide emissions from the fossil fuels that would otherwise have been used. Methane can be used directly as gas or used to generate electricity and be sold to the grid.

Electricity generation makes up about three-fourths of currently operational landfill gas capture projects in the United States. Besides the revenue from electricity sale, creation of new jobs associated with the design, construction, and operation as well as air quality improvement are other benefits of landfill gas utilization. While there are lots of environmental and economic advantages, from a technical point of view, utilization of landfill gas for energy presents technical challenges due to low and fluctuating energy content which results in flame instability.

One of the methods of catalytic reforming of portion of landfill gas and an experiment conducted to validate it are described in Chapter 2 of this research. A mixture of Hydrogen and Carbon Monoxide (syngas) was injected at the different ratios to the stream of landfill gas and the resulting gas mixture was then introduced to an internal combustion engine. Results were measured in terms of exhaust emissions and engine performance at different ratios of landfill gas and syngas.

Despite the difficulties with laboratory equipment, this experiment proved that the addition of syngas to Landfill gas changes characteristics of combustion process and results in increased reactivity of the fuel mixture and decreased exhaust emissions.

Review of waste management in Russia and in Moscow: In Appendix D of this report (p.41 et seq.), the author reviews briefly the current state of waste management in Russia and the means of disposal of municipal solid waste in the metropolitan area of Moscow.

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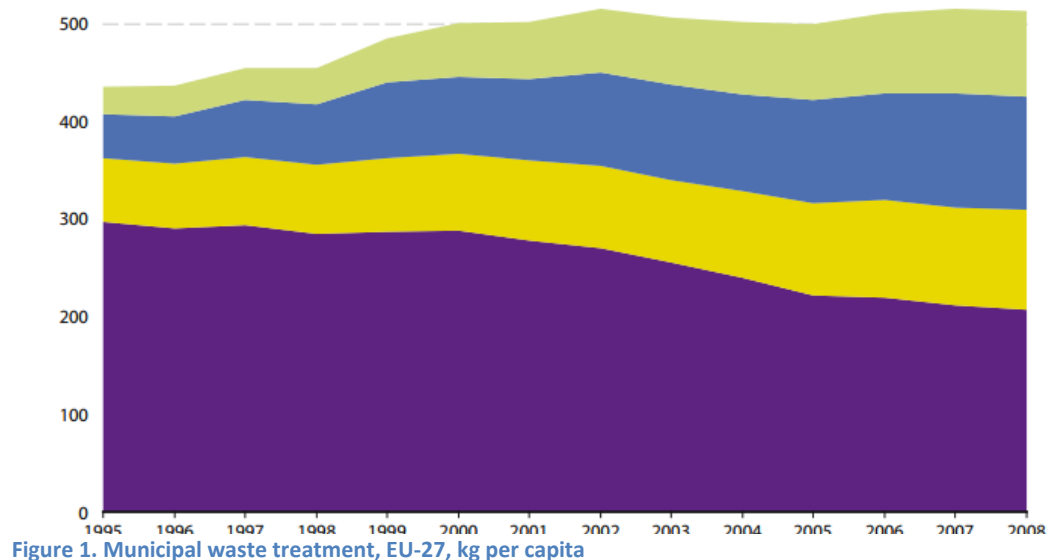
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## Chapter I. Current state of Landfilling and Landfill gas usage analyses

### I.1. Municipal Solid Waste in the World

The current annual world Municipal Solid Waste (MSW) generation, estimated by D-Waste is 1.9 billion tons with almost 30% of it going uncollected. Of the collected MSW, 70% is taken to landfills and dumpsites, 19% is recycled or recovered and 11% goes to energy recovery facilities [1]

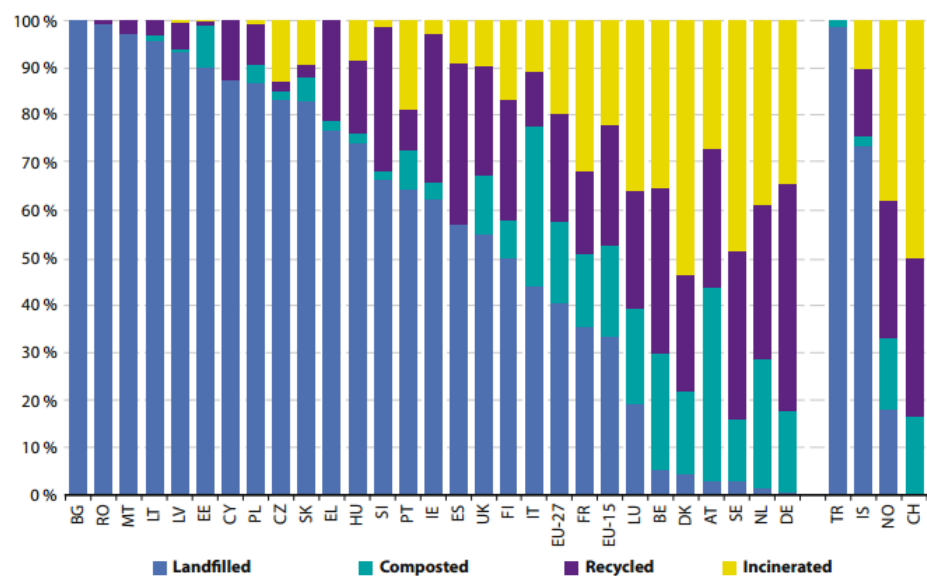
Of the total amount of waste treated in European Union-27, disposal, which includes landfilling as well as land treatment and release into water bodies, represents slightly more than 50% [21]. The other main waste treatment options are incineration, energy recovery and material recovery. In some European countries, restrictions on the landfill of certain types of waste have been imposed and much more waste is now recovered or incinerated.



Source: Eurostat

Currently Belgium, Denmark, Austria, Sweden, Nederland and Germany manage municipal solid waste systems to minimize landfilling resulting in

less than 10% of their waste stream going to landfill. Austria emphasizes composting organic waste; while the other five countries incinerate majority of their waste. Other European countries lag behind the six leaders, with landfilling rate of more than 90%. Among those countries are Bulgaria, Turkey, Romania, Malta, Latvia and Lithuania. Reviewing this data reveals that that counties incinerating their waste, are also the ones with higher rates of recycling and composting. Countries with no waste to energy are most likely to have very little or no recycling and composting .



Source: Eurostat, 2012

Figure 2. Municipal Solid Waste treatment, EU-27, % of total

## I.2. Municipal Solid Waste in the USA

The majority of the world's municipal solid waste is still going to the landfill even in the most economically developed countries, including the US. The actual amount of MSW generated in the US is still subject to debate. According to the latest EPA data, there was 250 million tons of MSW generated in 2008, while BioCycle and Earth Engineering Center cites much higher numbers of 390 million tons generated and 270 million tons being landfilled[4].

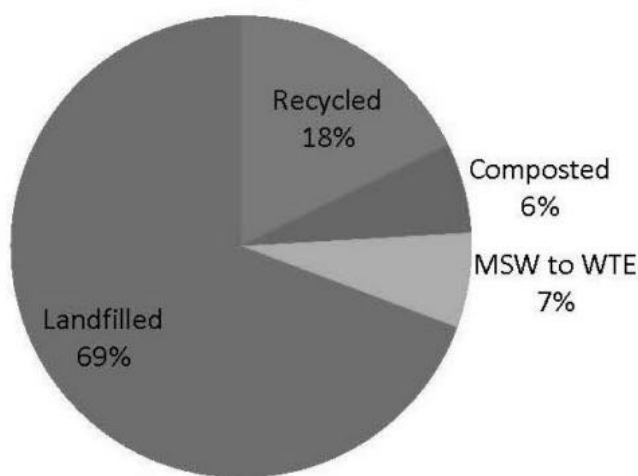


Figure 3. Management of MSW in the US

Source: *BioCycle 2010* [4]

Disposing of solid waste in modern, managed landfills is the most commonly used waste management technique in the United States. Disposing of waste in illegal dumping sites is not considered to have occurred in years since 1980 and these sites are not considered to contribute to net emissions in this section for the inventory time frame of 1990 to 2011. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil, clay or other material. There are numerous environmental monitoring systems

implemented at sanitary landfills to track performance, collect and neutralize leachate, and collect landfill gas.

The United States is at a critical juncture in its energy portfolio. There is renewed attention to producing energy domestically, reliably and environmentally responsibly. Bringing new energy online to meet projected demand will require a combination of conventional sources with an increased contribution from renewable, distributed sources such as wind, solar and biomass. In addition low quality (low BTU) and unconventional fuels are increasingly being considered. Two significant issues with using low quality and unconventional fuels are the combustion performance and the emissions generated. One example of a low quality, unconventional fuel is landfill gas (LFG), a significant source of energy from municipal solid waste (MSW). The average MSW generation per capita is nearly 5 pounds per day. If that waste is converted to energy it has the potential to offset approximately 20% of oil imports.

Nearly 70% of MSW goes to landfills (see figure 3) where it anaerobically decomposes to produce mostly CH<sub>4</sub> and CO<sub>2</sub> gas in a one-to-one ratio. Capturing that gas for landfill gas-to-energy (LFGTE) projects turns landfills into a source of clean, renewable energy and has been demonstrated on a commercial scale. However, many small and mid-sized landfills are prevented from installing LFGTE projects by the low and/or fluctuating BTU content of the LFG resulting in poor combustion performance and increased emissions.

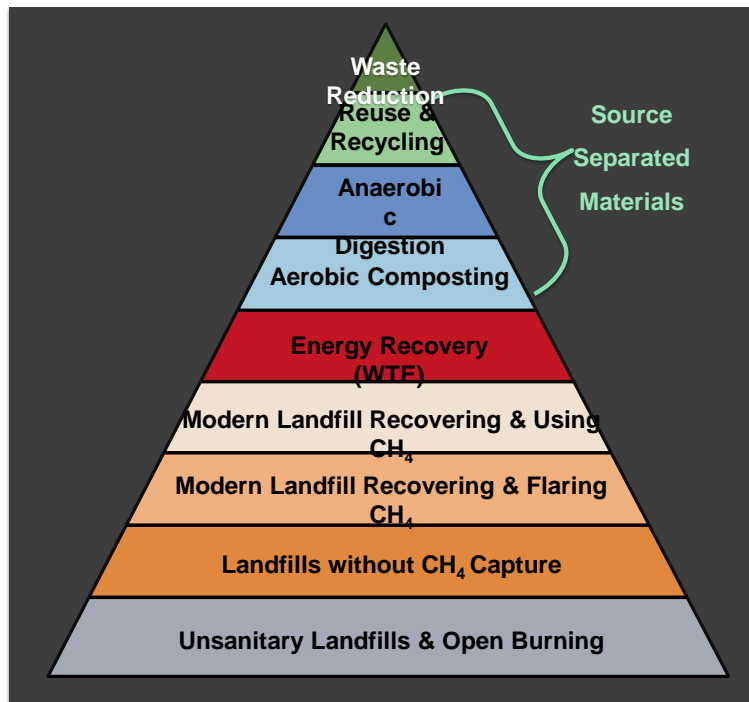


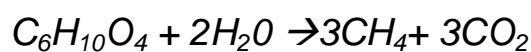
Figure 4. Waste hierarchy, IPCC

There are only two proven methods to dispose of MSW at the rate it is generated – landfill and waste-to-energy. The extraction of materials and energy from MSW must be done to achieve sustainable practices in managing and disposal of waste. The hierarchy of waste management, fig 4, shows that after reduce, reuse and recycle, energy extraction is the next best disposal method. Energy extraction can come from gas collection of composting the organic fraction of the waste or from landfills (yielding 120 MWh/ton) or combustion of MSW (yielding ~620 MWh/ton). As consumer awareness of environmental issues and the demand for renewable energy such as LFGTE increase, LFGTE projects are becoming especially valuable to utilities and thus require continued development.

### I.3. Landfill gas feasibility

Because of the presence of organic content in the landfilled waste, landfill gas and leachate are generated by the process of anaerobic decomposition. To be more specific, after being placed in a landfill, organic waste is initially decomposed by aerobic bacteria. After the oxygen has

been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria [19]. These Methane-producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic Carbon Dioxide and 50 percent Methane, by volume.



Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition by-products or volatilization of biodegradable wastes [19]. See figure 5. It also contains trace amounts of ammonia and sulfides, both of which cause unpleasant odors even at very low concentrations.

Landfill gas composition is highly dependent on climate at the landfill location, season, landfill conditions and age, type of landfilled waste and moisture content. However, regardless of the local conditions, almost half of the generated gas is methane. Methane is well known as Green House Gas (GHG). Despite the fact that Methane's lifetime in the atmosphere is much shorter than Carbon Dioxide, Methane is much more efficient at trapping radiation than Carbon Dioxide. The comparative impact of Methane on climate change is over 20 times greater than that of Carbon Dioxide over a 100-year period [3]. If uncontrolled, Landfill Gas contributes to smog and global warming, and may cause health problems.

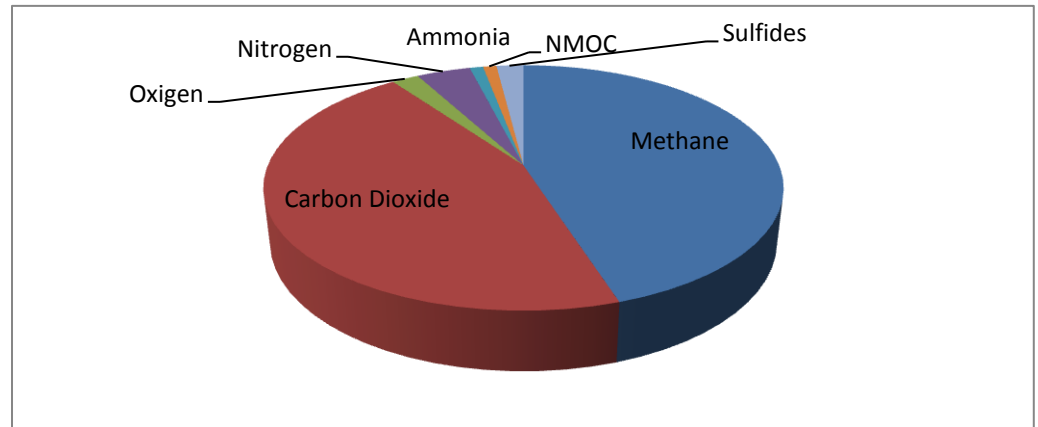


Figure 5. Landfill gas composition

But at the same time, landfill gas is a potential alternative energy source. Landfill Gas to Energy (LFGTE) process has attracted a lot of interest as a source of energy and heat with an additional benefit of reducing methane emissions into the atmosphere. One ton of biodegradable waste produces between 50 m<sup>3</sup> and 270 m<sup>3</sup> of landfill gas. [14], [15],[20].

Collection and use of Landfill gas should not be considered as the best Waste-To-Energy way in every country where landfilling is used. The diversion of biodegradable municipal waste from landfill is a key objective under the European Union landfill directive. This directive aims to reduce negative impact of landfilling waste on the environment and requires Member States to reduce the amount of biodegradable waste going to landfills in order to reduce methane emissions. The goal of the directive is to achieve a 50% reduction of landfilled biodegradable waste by 2013 and 65% reduction by 2020 as measured against the 1995 levels [22]. The emphasis on composting and other technologies to deal with this waste stream is growing in European Union. However, this reduction in organic material reaching the landfills will also reduce the methane stream available to LFGTE projects in the EU by as much as 1/3 making them economically unfeasible by 2020.

Until there is no separate collection and recycling of the organic waste stream in the US, landfill gas to energy projects will remain feasible.

#### I.4. Landfill gas utilization

US laws requiring collection of landfill gas are not based on global warming impact of methane, but rather on the toxic hazards of NMOCs. Federal regulations require that landfills with total permitted capacity greater than or equal to 2.5 million cubic meters of waste, to have their annual Non-Methane Organic Compound emissions estimated. If the NMOCs are estimated at more than 55 tons per year, the landfill must adhere to rules that include submitting compliance reports and install a gas collection system [3].

LFG electricity projects capture ~85% of the methane emitted from a MSW landfill. In addition to reduced price volatility, an LFG to electricity project provides two GHG emissions reduction opportunities. First, it requires methane from the landfill to be collected, thereby preventing the gas from escaping into the atmosphere. Second, it displaces the CO<sub>2</sub> emissions from the fossil fuels that would otherwise have been used. There are other broader benefits such as air quality improvement of the surrounding community by reducing landfill odors. LFGTE projects generate revenue from the sale of the electricity and create jobs associated with the design, construction, and operation of energy recovery systems that include engineers, construction firms, equipment vendors, and utilities or end-users of the power produced. Much of this cost is spent locally for drilling, piping, construction, and operational personnel, helping communities to realize economic benefits from increased employment and local sales. Besides electricity production, gas, captured from Landfills can be used directly. Landfill gas can offset the use of fossil fuel thus reduce current dependency rate from primary energy sources. It also can be used on the landfill itself to evaporate leachate. Innovative direct uses include firing pottery and glass-blowing kilns; powering and heating greenhouses and an ice rink; and heating water for an aquaculture (fish farming) operation [2].

Another benefit of LFGTE is education and increasing of public awareness of positive sides of Landfills and of waste treatment in general. A lot of people may not be aware of environmental benefits of waste to energy projects and suppose that everything beyond recycling is not environmental friendly. Implementing LFGTE projects increase public awareness and make people from local community become familiar with environmental friendly engineered waste treatment.

### **I.5. Landfill gas to energy in the US**

Currently there are 621 operational LFGTE projects in the US generating 1,978 MW and 311 mmscfd. There are also about 450 LFGTE candidate landfills, which are expected to create additional 850 MW or 470 mmscfd [12]. There are two maps representing direct usage of Landfill gas (see fig 7) and electricity generation LFGTE projects (see fig 6) in the US. Colored background of both maps represents population density, where blue is the lowest and red is the highest. Each county with a LFGTE project allocated in that map is bordered in green color. The diameter of the circles represents power output, fig 6, and gas generation, fig 7.

The generation of electricity from LFG makes up about three-fourths of the currently operational projects in the United States, see the distribution of those projects of the map- fig 6. The bigger the diameter- the more megawatts are generated from landfill gas combustion. From maps it is easy to see how LFGTE projects located where the population is the densest. LFGTE projects require both, source of waste as big landfill and a market for the product- power or gas. That is why there are projects located next to the biggest cities in the country: New York great area, Chicago area, Los Angeles and San Francisco areas and Dallas.

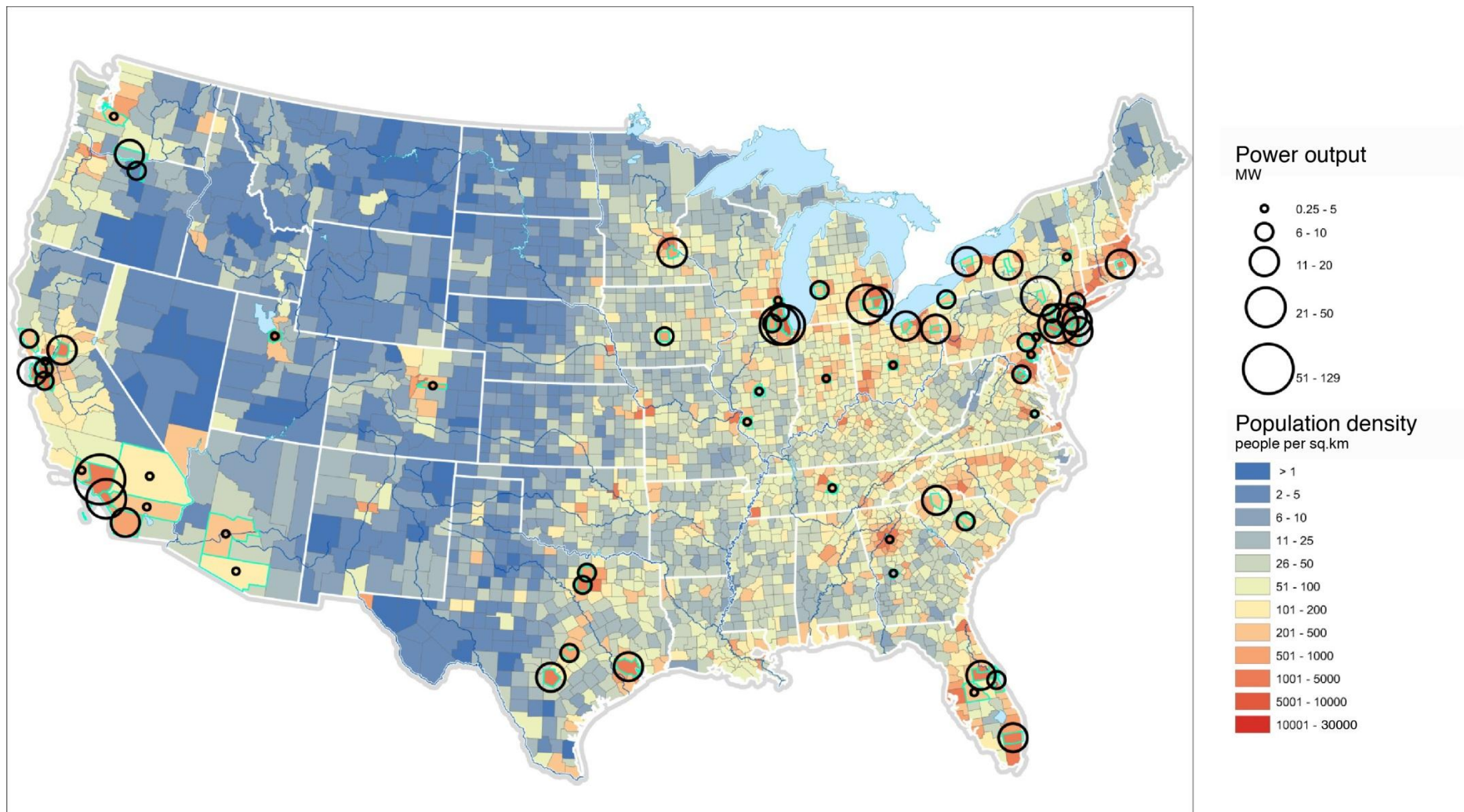


Figure 6. Distribution of electricity generation capacity from LFGTE

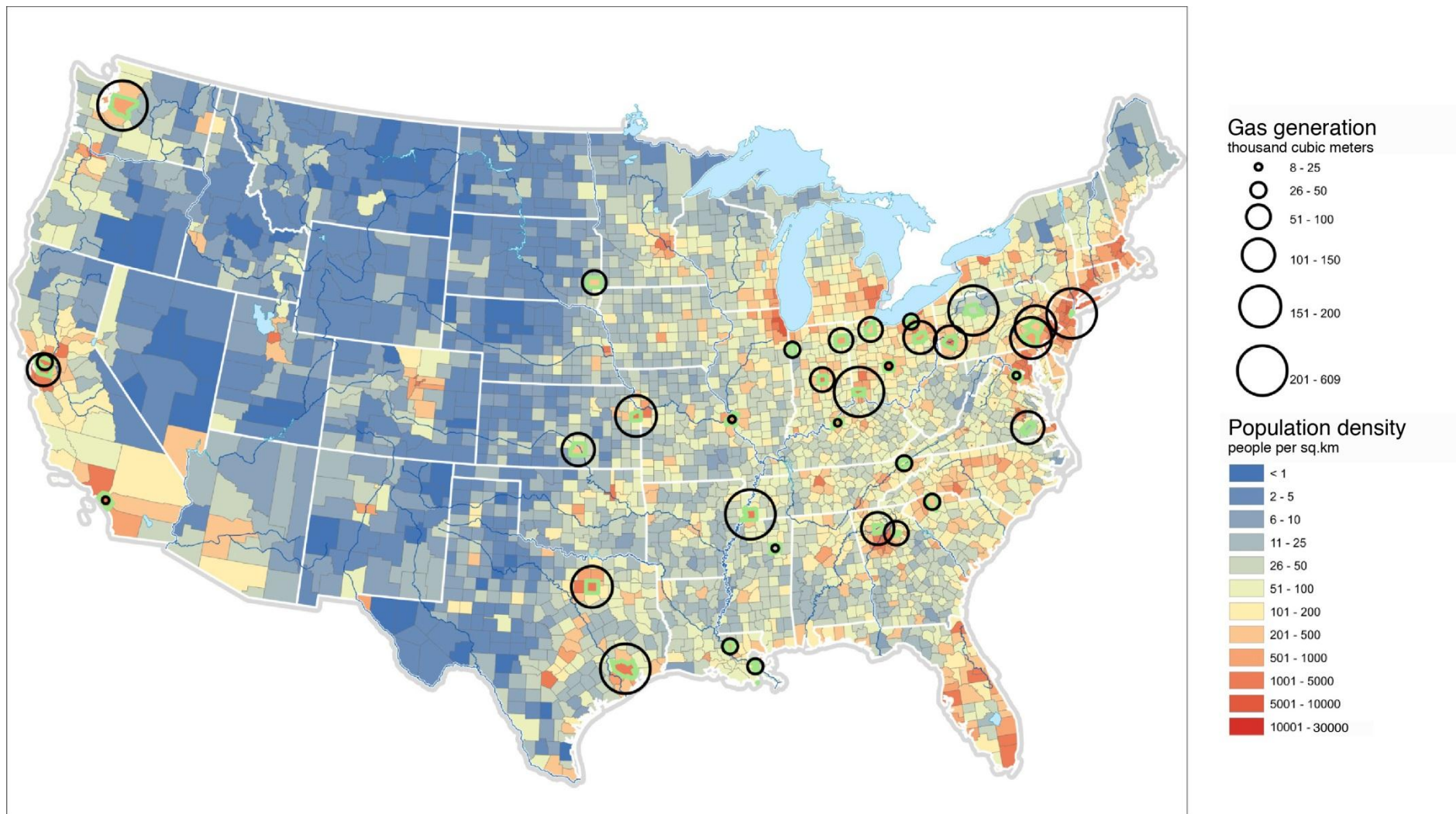


Figure 7. Distribution of gas generation capacity from LFGTE

## I.6. Classification of landfill gas usage projects

EPA classifies LFGTE projects into four categories: direct use of gas, electricity generation, cogeneration and upgraded. The majority of LFGTE projects generate electricity from landfill gas. Syngas addition into landfill gas stream it is not a method that is currently implemented. Syngas addition will fall into EPA category of upgraded use of landfill gas.

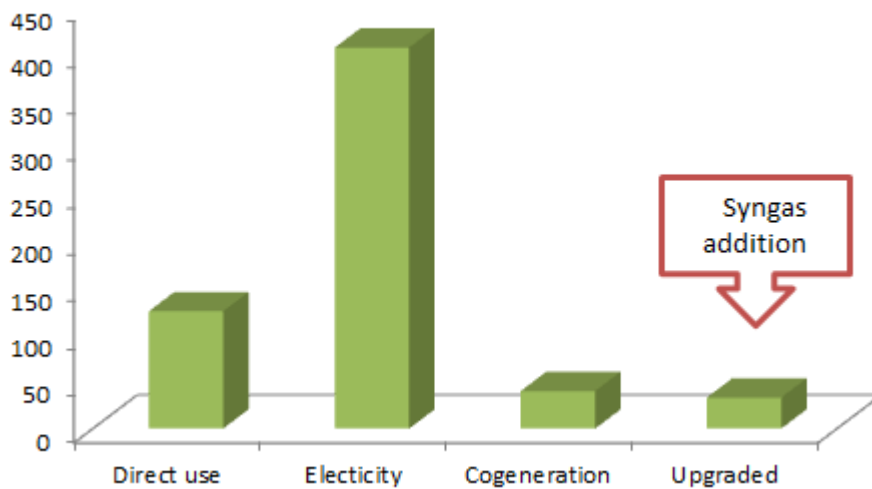


Figure 8. Classification of LFGTE projects [12]

There are 147 operation LFGTE projects located in Tri-state area, which is associated with states of New York, New Jersey and Pennsylvania. All together they generate 290 megawatt of power. About a quarter of the projects are currently closed and a little more than a half is governmental owned.

Electricity from landfills gas be generated using a variety of different technologies, including internal combustion engines, turbines, microturbines, and fuel cells. The majority of projects use internal combustion engines or turbines, with microturbine technology being used at smaller landfills. Technologies such as Stirling and organic Rankine cycle engines and fuel cells are still in development.

Nowadays there are a lot of applications for direct use of landfill gas. Current industries using LFG include auto manufacturing, chemical

production, food processing, pharmaceuticals, cement and brick manufacturing, wastewater treatment, consumer electronics and products, paper and steel production, and prisons and hospitals [12].

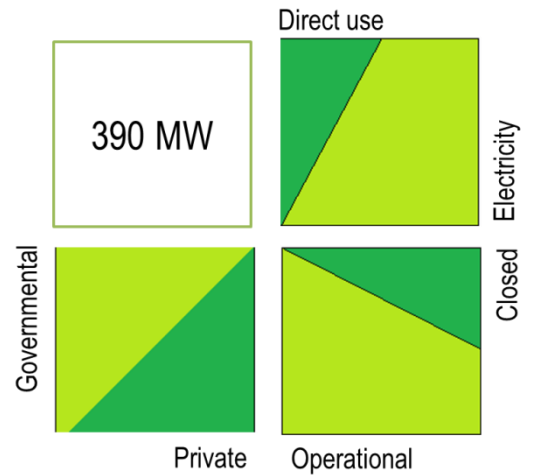


Figure 9. Tristate area LFGTE projects breakdown

### I.7. Method of the catalytic reforming a portion of LFG

There are difficulties in using LFG for energy because of low and fluctuating energy content resulting in lack of flame stability. That results in decreasing of fuel efficiency and increased CO, unburned hydrocarbon (UHC), and NO<sub>x</sub> emissions. To mitigate these emissions, there are many conventional post combustion cleanup methods. However, many of these methods result in reduced power output due to pressure drop increases and could potentially add significant expense. Typically, emission waivers are required before LFGTE projects can be permitted [6].

One method of increasing the reactivity of LFG and reducing engine emissions is to add hydrogen to the fuel stream. In this study, injection of syngas, a mixture of H<sub>2</sub> and CO, is investigated as a method of reducing engine emissions and increasing engine efficiency.

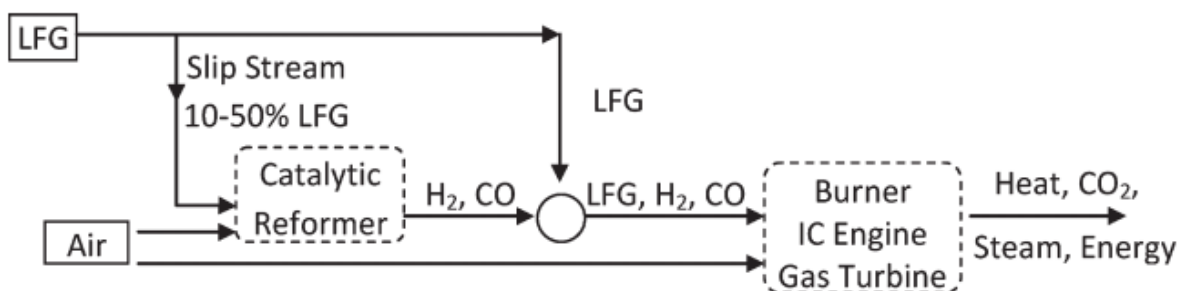


Figure 10. Schematic of partial catalytic reforming of LFG [6].

## II. Chapter 2. Experiment

The Combustion and Catalysis Laboratory (CCL) has demonstrated that landfill gas can be fully converted to syngas using a Rh/Al<sub>2</sub>O<sub>3</sub> catalyst for both dry and auto-thermal reforming even in the presence of LFG chlorine impurities. Dry reforming is the direct conversion of CH<sub>4</sub> and CO<sub>2</sub> into H<sub>2</sub> and CO, while auto-thermal reforming includes the addition of air. The benefit of air addition is that it enables the exothermic reactions of methane combustion and partial oxidation to supply heat for the reforming reactions, resulting in lower heat input, or possibly zero external heating (i.e. autothermal operation).

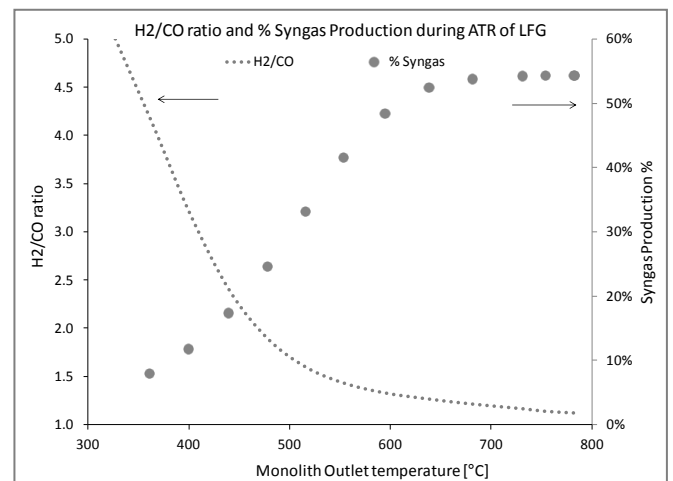


Figure 11. Syngas production and H<sub>2</sub>/CO ratios obtained while auto-thermally reforming a 1:1:0.5 CH<sub>4</sub>:CO<sub>2</sub>:O<sub>2</sub> gas mixture as a function of monolith outlet temperature [6]

Figure 11 shows the amount of syngas production and the H<sub>2</sub>/CO ratios obtained while auto-thermally reforming a simulated landfill gas with a CH<sub>4</sub>/CO<sub>2</sub> ratio of one. H<sub>2</sub>/CO ratio is shown on the primary ordinate and syngas production is shown on the secondary ordinate as a function of monolith outlet temperature (abscissa). This data demonstrates that LFG can be reformed to produce syngas at various H<sub>2</sub>/CO ratios and concentrations as a function of the temperature of the catalyst.

The CCL has also demonstrated that syngas introduction into an IC engine operating on LFG reduces emissions and improves the engine efficiency. Figure 12 below shows the performance of a 2.8 kW (5-hp), 4 stroke Honda GC 160E engine operating on simulated landfill gas (SLFG) compared to SLFG with 10% addition of syngas with a H<sub>2</sub>/CO ratio of one. The engine testing showed that injecting up to 5% syngas into a simulated LFG mixture prior to entering a combustion engine decreases CO, UHC, and NO<sub>x</sub>

emissions by 73%, 89%, and 38%, respectively, and increases engine efficiency by 10% [6]. Therefore syngas addition clearly improves the combustion efficiency of an IC engine operating on LFG and opens opportunities for the conversion of low-BTU LFG or other CH<sub>4</sub>/CO<sub>2</sub> mixtures to energy.

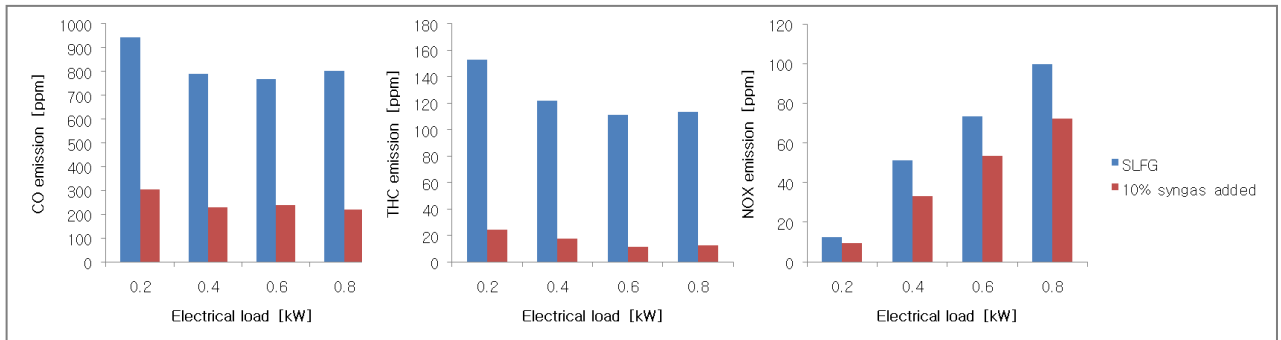


Figure 12. CO, THC, and NOx Emissions of a 2.8 kW 5hp 4 stroke Honda GC 160E engine operating on simulated landfill gas (SLFG) compared to SLFG with 10% syngas addition [6]

## II.1 Intention

The intent of this experiment is to make a contribution to the global waste to energy research in the area of municipal solid waste combustion reaction. The experiment conducted during this research was performed to examine the use of landfill gas with the addition of syngas (H<sub>2</sub> and CO) in the internal combustion engine. The points of interest were the exhaust emissions and engine performance at different electrical loads. It is expected that syngas would be produced by a catalyst installed close coupled to an engine where it will reform a portion of the landfill gas. In the experiment, all gases were obtained from cylinders and mixed in the surge tank directly connected to the engine.

## II.2. Equipment and specifications

### Engine

In this study, the experiments were performed using a Honda 5 hp, 160cc, single cylinder, four-stroke, spark-ignition gasoline engine. See original engine picture Figure 13.

The engine was originally fueled by gasoline. It was retrofitted for use with gaseous fuels such as methane. The carburetor, fuel tank, and fuel pump were removed from the engine. An aluminum plate with a 1/2 inch threaded hole for pipe fitting was fabricated and fixed to the engine in order to directly feed the mixture of fuel and air into the engine cylinder. Between the plate and cylinder wall, a graphite gasket was installed to prevent leakage of fuel and air mixture. See Figure 14.

The muffler, which is used to reduce engine noise, was removed, and a metal plate with a threaded hole was installed on the exhaust outlet. A tee was fitted on the added exhaust pipe so that the analyzer was only drawing off a sample of the exhaust and not receiving the full exhaust flow.



Figure 13. Original Honda engine

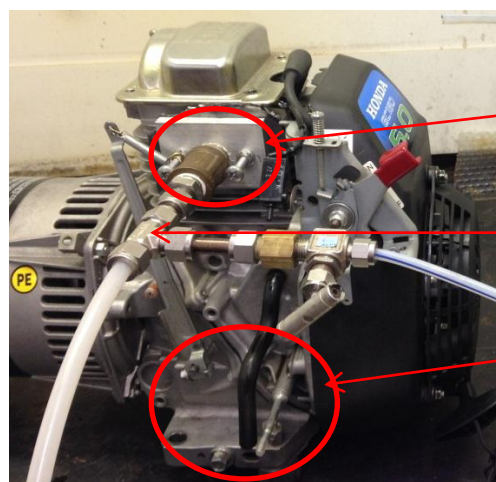


Figure 14. Retrofitted Honda engine

Graphite gasket  
Gaseous fuel pipe  
Removed fuel tank

### Generator, Emission analyzer

The engine was directly connected to a PRAMAC EG2800 electric generator. This generator is shown in Figure 15. Emission analysis, Figure 16, was conducted with ENERAC integrated emissions system Model 700.



Figure 15. PRAMAC EG2800 generator



Figure 16. ENERAC 700

The probe of the Enerac was inserted into the exhaust pipe. With analyzer in operation, the pump inside the device withdrew a sample of the exhaust gas. This sample was conditioned before entering the analyzer, via an onboard water trap. A number of sensors in the ENERAC 700 analyzed the contents of the stack gas, calculated and displayed the results.

Electrochemical sensors (SEM) measured the Carbon Monoxide, Nitric Oxide, Nitrogen Dioxide and Oxygen gases. These SEM sensors consisted of two components: the sensor module and the precision control module (PCM). The function of the PCM is to set the sensitivity of the sensor and also to contain any filter material that removes the effect of interfering gases. Non-dispersive infrared spectroscopy (NDIR) sensors are also included in the ENERAC 700. The NDIR bench operates on the principal that different gases absorb infrared radiation at varying frequencies. The NDIR bench could then measure Carbon Monoxide, Carbon Dioxide, and Unburned Hydrocarbons

## Power meter

To measure the power output produced by electric generator , a Wattsup pro power meter was used. A current transformer was used to step down the current by a factor of ten so that the meter's current rating was not exceeded. Figure 17 and 18 shows the power meter and the circuit diagram of the load board and meter assembly.



Figure 17. Wattsup Pro power meter

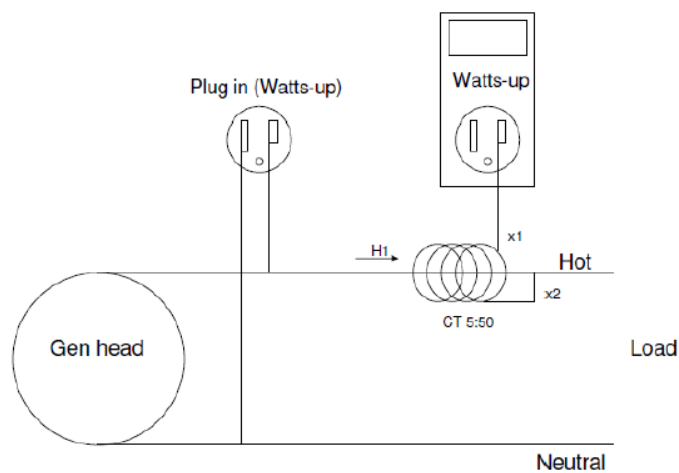


Figure 18. Circuit diagram

### II.3. Schematic and description

The engine connected to the generator was fueled by simulated landfill gas. Four gases were mixing in a surge tank with house air. Final fuel mixture was fed to the engine to be burned. The emissions were then measured on the exhaust side. The generator was connected to an electric load consisting of several light bulbs 100 watts each to provide variable engine load. All gases were taken from the cylinders (gas purity) and were measured and controlled by rotameters. House air was controlled by pressure regulator and measured by air flow meter. The electric power generated by the engine-generator system was measured by the Wattsup Pro powermeter as an indication of engine load and performance. Exhaust emissions such as carbon monoxide, unburned hydrocarbon, and oxides of nitrogen (as the sum of nitrogen oxide and nitrogen dioxide) were analyzed by an Enerac 700 integrated gas analyzer. The Enerac was displayed on the computer with the help of Enercom software.

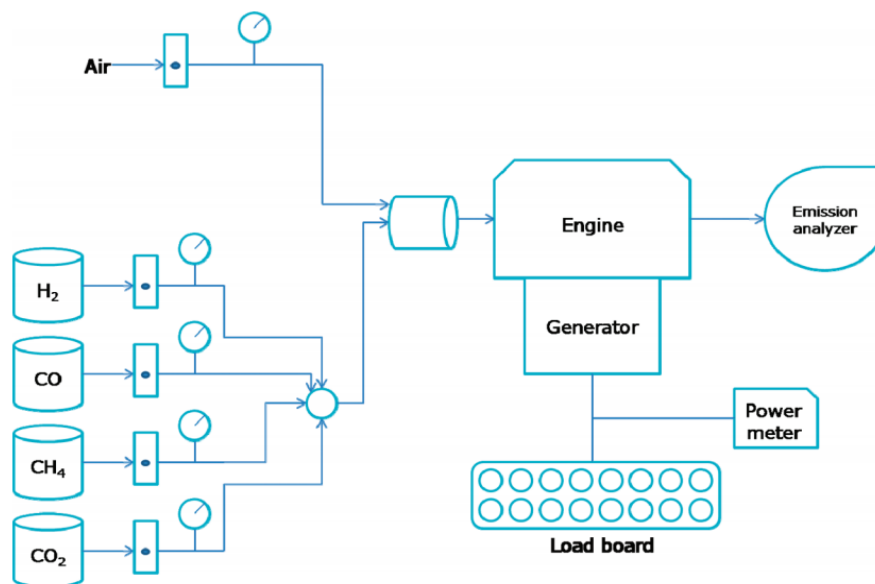


Figure 19. Experiment schematic

## II.4 Experiment procedure

### TURNING ON THE ENGINE

1. Before each test the ENERAC 700 was zeroed for 100 seconds.
2. The ENERAC 700 was connected to a computer to record data.
3. The fume hood in which the engine experiment carried out was turned on.
4. Tube connections from gas sources to each rotameter, from each rotameter to pressure gauges, and to the mixing chamber and engine were closely checked and tightened.
5. The air flow to the engine was turned on.
6. The rotameter value for air was monitored and flow was adjusted appropriately.
7. The delivery pressure regulator for air was set at 30 psi
8. The system was checked for leaks on the air line with soaped water.
9. The CH<sub>4</sub> flow was turned on.
10. The delivery pressure for methane was set at 20 psi
11. The rotameter value for CH<sub>4</sub> was monitored and flow was adjusted appropriately.
12. The system was checked for leaks on the methane line with soap water.
13. The engine was started.

### FLAWS REGULATION

- 
14. The CO<sub>2</sub> flow was turned on (if required by the specific test).
  15. The rotameter value for CO<sub>2</sub> was monitored and flow was adjusted appropriately (if required by the specific test).
  16. The system was checked for leaks on the carbon dioxide line with soap water.
  17. The CO flow was turned on (if required by the specific test).
  18. The rotameter value for CO was monitored and flow was adjusted appropriately (if required by the specific test).
  19. The system was checked for leaks on the carbon monoxide line with soap water.
  20. The H<sub>2</sub> flow was turned on (if required by the specific test).
  21. The rotameter value for H<sub>2</sub> was monitored and flow was adjusted appropriately (if required by the specific test).
  22. The system was checked for leaks on the hydrogen line with soap water.
-

LOAD&PROBE	<p>23. A number of bulbs on the load board were turned on.</p> <p>24. 15 minutes were allowed to pass so that steady state was reached.</p> <p>25. A probe connected to the gas analyzer was put into the center of exhaust pipe.</p> <p>26. 10 minutes were allowed to pass until data from the gas analyzer stabilized.</p> <p>27. Gas analyzer data recording was started on the computer during the next 10 minutes.</p> <p>28. The probe was removed from the exhaust pipe.</p>
REPEAT	<p>29. When the electrical load, the fuel or air flow were changed, the above procedure was repeated from the beginning.</p> <p>30. Each experiment was repeated three times to calculate the mean values of the experiments.</p>
TURNING OFF	<p>31. The bulbs on the load board were turned off.</p> <p>32. The CH<sub>4</sub> flow was turned off, engine stopped.</p> <p>33. The CO flow was turned off.</p> <p>34. The H<sub>2</sub> flow was turned off.</p> <p>35. The CO<sub>2</sub> flow was turned off.</p> <p>36. Air flow was turned off.</p>
FINILIZING	<p>37. The ENERAC 700 was allowed to draw in ambient air until all emission values approached 0 ppm.</p> <p>38. The fume hood was turned off.</p> <p>39. When all values on the ENERAC 700 reached zero, the device was turned off.</p> <p>40. It was checked to make sure gas cylinders were completely closed and gas remaining in pipeline was vented.</p>

## II. 6. Safety

Laboratory experiments are always associated with a risk. Because of that, safety is a main priority during the experimental research.

Chemical reaction of combustion is a rapid oxidation, which transforms energy stored in the chemical bonds to the heat that can be utilized [8]. In that experiment, energy from 3 flammable gases- methane, hydrogen and carbon monoxide are being used. Characteristics of the gases see table 1.

Table 1. Gases characteristics

Gas	Flammable	Auto-ignition Temperature	Toxicity	LEL-UFL	Symptoms
CH <sub>4</sub>	Yes	580 C 1076 F	relatively non-toxic	5 - 15	headache, heart palpitations, dizziness, fatigue
H <sub>2</sub>	Yes, extremely	500 C 932 F	Non toxic	4 - 75	headaches, ringing in ears, dizziness, drowsiness, unconsciousness, nausea, vomiting and depression of all the senses. The skin may have a blue color
CO	Yes	609 C 1128 F	25 ppm	12,5 - 74	headache, drowsiness, dizziness, nausea, confusion
CO <sub>2</sub>	No	-	5000 ppm	-	headache, flushed skin, full pulse, shortness of breath

Leaking of flammable gases can cause unwanted ignition. Sources of ignition for leaked Hydrogen, Carbon Monoxide and Methane are the engine, generator, and light board. The rotameters of all gases are kept at the distance from all of those sources and located on the separated table to reduce risk of ignition. Before the test, each line has been tested for leaks with soapy water. During the operation, the lines were closely monitored.

There are some conditions for that experiment at which concurrent flow can occur. The delivery pressure for house air are usually 25-30 PSI while flammable gases from the cylinders were delivered at constant 20 PSI pressure. The air can flow against the current of influent gas and into the original source of gases. It is dangerous for air to enter flammable gas lines and especially the Hydrogen cylinder, as the combination of highly pressurized oxygen and hydrogen would practically create a rocket. To prevent this from happening, two check valves were installed upstream of the surge tank, one in the fuel line and the other in the air line. Each gas line was equipped with check valves so no flow can get to the cylinders.

If the engine gets not sufficient amounts of air or fuel, it will stall. This will cause a large pressure build-up in the engine, and if large enough, the fuel or air will flow against the current. As there are check valves on the surge tank, the pressure will build up in the line between the surge tank and engine. The emergency exhaust line with a on-off valve were installed right after the surge tank. The cross was installed down the line to provide second emergency exhaust. This way any countercurrent flow would stop at the surge tank inlet and pressure will be release in the line.

If the leak is happening and not detected by soapy water, there are 2 detectors located around the set up. As long as Methane – 16 g/mol and Hydrogen – 2g/mol are lighter than air, the detectors are located above the set up on the wall.

When the experiment runs, the fire extinguisher is located next to the set up. All the cylinders are secured according to the training provided by the office of the environmental health and occupational safety. Power cords are separated from the gas lines. Heat proof glove is used since the engine gets hot very quickly.

To eliminate the risk of working in the lab, the team of senior students and doing a Test Readiness Review for the upcoming experiment. Having a fresh look to the set up and answer critical questions is always very helpful in terms of safety concern.

For the experiment held in that research work, the test readiness review TRR was held June, 30th 2014. See TRR issues and solutions outline see in the Appendix B.

## II.7. Calculations

Before experimental part began, fuel flows were calculated for each electrical load.

From the engine specifications it is known that before engine was retrofitted, it's fuel consumption was 0.313 kg/kWh. Low Heating Value (LHV) of gasoline which was meant to be used in the engine is 44.3 MJ/kg.

1 kWh = 3.6 MJ, thus fuel consumption is

$$\frac{0.313kg}{3.6MJ} = 0.087 kg/MJ$$

In other words, 1 kg of fuel gave an energy output

$$\frac{1 kg * MJ}{0.087kg} = 11.4 MJ$$

While energy that was going in from 1 kg of gasoline is 44.3MJ

Thus, the Engine Efficiency is energy output divided by energy input.

$$\frac{11.4 MJ}{44.3 MJ} = 0.25 = 25\%$$

It is important to know engine efficiency to find amount of methane, needed for each electrical load experiment. Desired Thermal output of the system depends on the engine efficiency and will require more input in terms of fuel.

$$\frac{W}{\text{engine efficiency}} = Q_{\text{thermal}}$$

for instance with the electrical load, is 0.4 kW, then required

$$\frac{0.4kw}{0.25} = 1.6kW_{\text{thermal}}$$

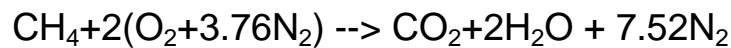
This requirement shall be fulfilled by methane, (LHV = 50029.6 kJ/kg), thus fuel flow equals Thermal output divided by enthalpy.

$$n = \frac{Q}{LHV(CH_4)}$$

$$n = \frac{1.6kW}{50029.6 kJ/kg} = 0.03 \frac{g}{s} = 2.6 L/min$$

See the results table2

The theoretical air required to complete methane combustion results from the equation of stoichiometry of oxygen/fuel reaction.



Stoichiometric air means the exact amount of air required by a stoichiometrically balanced equation. The stoichiometric air/fuel ratio (AFR) can be calculated from the reaction equation. 1 mole of Methane requires 2 moles of Oxygen and 2 times 3.76 mole of Nitrogen, thus AFR = 2+7.52 = 9.52

The actual combustion air depends also on the assumed air excess (equivalence ratio or stoichiometric ratio)[10]. Using equivalence ratio consistent =0.5 by formula below actual air needed for the combustion reaction was found:

$$\phi = \frac{\left(\frac{fuel}{oxid}\right)_{actual}}{\left(\frac{fuel}{oxid}\right)_{stoic}}$$

$$\left(\frac{fuel}{oxid}\right)_{actual} = \phi * \left(\frac{fuel}{oxid}\right)_{stoic}$$

$$oxid(actual) = \frac{fuel(actual)}{\phi * AFR}$$

$\left(\frac{fuel}{oxid}\right)_{stoic}$  is the stoichiometric fuel to oxidizer ratio and the  $\left(\frac{fuel}{oxid}\right)_{actual}$  is the actual fuel to oxidizer mass ratio. The results for each load see in the Table2.

Table 2. Methane and air flow as a factor of load, based on calculations

Load:	Methane	Air
kW	(L/min)	(L/min)
0.4	2.6	49.1
0.8	5.2	98.2
1.2	7.7	147.4

The addition of Syngas was made by calculated percentage of enthalpy of the reaction.

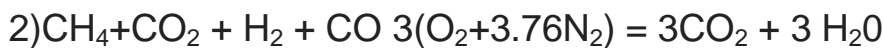
During the experiment three different combustion reactions were produced: combustion of methane, combustion of methane with carbon dioxide and combustion of methane with carbon dioxide and syngas.

The enthalpy of each of the reactions was found by the heat of formation [10]



$$H_{\text{comb}} = 2H^*\text{CO}_2 + 2H^*\text{H}_2\text{O} - H^*\text{CH}_4 - H^*\text{CO}_2 - 3H^*\text{O}_2 - 5.64\text{N}_2$$

$$H_{\text{comb}} = -802.2 \text{ KJ/mol}$$



$$H_{\text{comb}} = 3H^*\text{CO}_2 + 3H^*\text{H}_2\text{O} - H^*\text{CH}_4 - H^*\text{CO}_2 - 3H^*\text{O}_2 - 5.64\text{N}_2$$

$$H_{\text{comb}} = -1327 \text{ KJ/mol}$$



$$H_{\text{comb}} = H^*\text{CO}_2 + 2H^*\text{H}_2\text{O} - H^*\text{CH}_4 - 3H^*\text{O}_2 - 5.64\text{N}_2$$

$$H_{\text{comb}} = -802.2 \text{ KJ/mol}$$

As we see, the enthalpy of the reaction with carbon dioxide and without is the same because there is no heat (no enthalpy) in Carbon Dioxide.

However, presence of  $\text{CO}_2$  in the gas mixture causes changes in Adiabatic Flame Temperatures (AFT). As greater  $\text{CO}_2$  concentration – the lower AFT is, see table 3.

Table 3. AFT as function of CO<sub>2</sub> concentration

Fuel Type	AFT, (K)
100% CH <sub>4</sub>	1244
100% CH <sub>4</sub>	1251
50% CH <sub>4</sub> , 50% CO <sub>2</sub>	1206

Source: [10]

Because of the CO<sub>2</sub> presence in Landfill gas lowers AFT, partial reforming of LFG to Syngas will help to maintain a AFT. Using 802.2KJ/mol as a baseline enthalpy of the reaction, Syngas addition was calculated at 5, 10 and 15 % by enthalpy.

## II.8 Problems/fixes

After several full sets of experiments, the engine stopped and didn't turn on again. It was found that inlet tube is getting hot while trying to turn on the engine. As for trouble shooting, we detected 3 groups of potential problems: spark (spark plug or electrical connections to the spark), fuel/air ratio, or inner parts of the engine. First of all, number of different fuel/air ratios were put into the system and all the flows calculations were double checked. Removing and installing a new spark plug is far easy to accomplish because of no need to open the engine and take it apart, that is why it was changed next.

A spark plug is a device for delivering electric current from an ignition system to the combustion chamber. The spark work is to ignite the compressed fuel/air mixture by an electric spark. A properly gapped spark plug is necessary for a properly functioning engine. The gap size affects the spark plug's firing temperature, which has a direct relationship to the combustion of fuel and air in the engine. Also, the spark plugs can build up some soot on the contact points



Figure 20 Removed spark plug



Figure 21 Spark Plug conditions and damages

Removed spark plug was not seems damaged, ( see figure 20 however, according to the figure 21, the distance between the electrodes were less than required by engine specifications- 0.6-0.7 mm. Some ash deposits were observed. Ground electrode seemed a bit banded.

The new spark plug was purchased but it seemed to have the gap more than required by engine specifications. A blade-style feeler gauge was used to reduce the distance between electrodes.



Figure 22. Blade-style feeler gauge

Changing the spark plug didn't help to start the engine. The next step was to change the oil, because it was not changed since engine purchase.



Figure 23. Changing the oil

In the oil it was a lot of metal particular matter on the bottom. It looked very dark grey (fig 23), unlike dark brown used oil the car. A small sample bottle was taken while the rest went to Environmental Health and Occupational Safety Department.

After the oil was changed, the engine didn't start. It was decided to open the top cap of the engine.

Right under the cap there is a cam shaft system of the engine, see figure 24. In internal combustion engines working with pistons, the camshaft is used to operate poppet valves. The cam lobes force the valves open by pressing on the valve. The camshaft lifts the valve from its seat. The further the valve rises from its seat the more airflow can be released.

When the cap was opened it was detected the cam shaft of the inlet doesn't touch the valve stem in "up" position. At the same time, outlet cam shaft system was working fine with the valve on both "up" and "down" position.



Figure 24. Cam shaft inlet and outlet at 1 and 3 stroke position

It means that the inlet valve stuck in the position “closed” or almost “closed”, which didn’t let the engine to operate normally. To fix that problem, the valve stem was liberally lubricated and forced to move up and down. On the way up it moved with a very high resistance and brought some metal deposits on the valve stem neck, see figure 25.



Figure 25. Deposits, founded on the valve stem neck

The fact of metal particles occurred on the stem could indicate that the stem, made from stronger material, scratched the inner part of the stem corridor. One of the reasons of such happening could be that the stem was slightly bended. The other reason that could happen is that the inner parts of the engine shifted from the original positions because of the not initial intended usage of the engine.

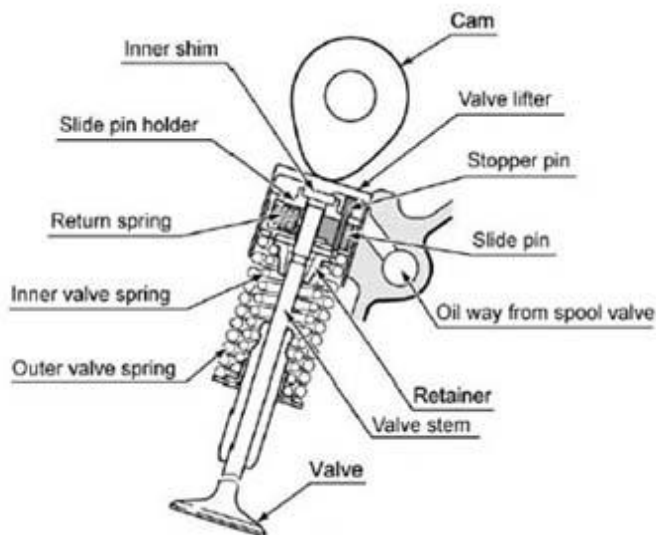


Figure 26. Cam shaft system schematic of IC Engine

## II.8. Results

The experiment performing combustion of Methane with addition of syngas was held on the same set up as Marcella Lusardi. Ms. Lusardi is a MS of Columbia University who performed an experiment on the same equipment. See more of here results in her Master Theses [10].

Tests 1 to 3 were made at the same conditions to get the most accuracy from averaged values. The results were compared with a baseline which is Emissions of Methane combustion performed by Ms. Lusardi. The conditions are: 400W load, 0% syngas. See results in Figure 27.

The main y- axis represents Carbon Monoxide and Hydrocarbons emissions in PPM, and Carbon Dioxide emissions in percentage of outgoing flow.

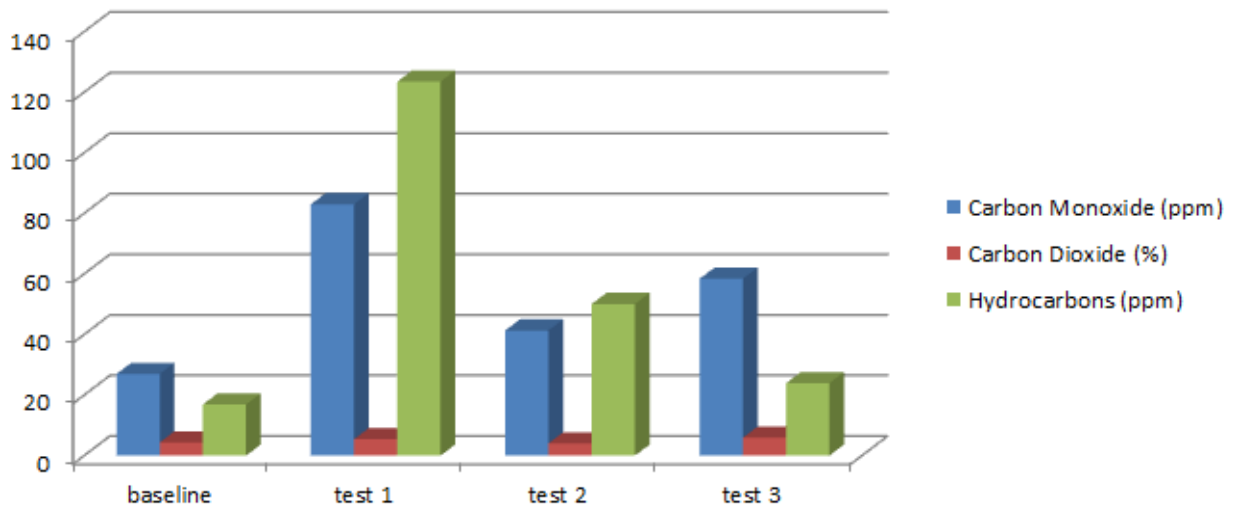
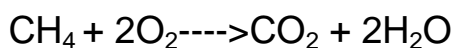


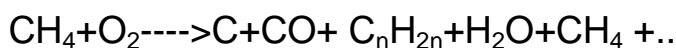
Figure 27. Methane Combustion Emission test results. 0.4kWreference

According to the data from the Enerac 700, Carbon Dioxide readings were slightly fluctuating from 4 to 6%. Carbon Monoxide data fluctuated from 40 to 80 ppm, which exceeds the baseline by 3 times. Hydrocarbons readings showed a significant change between the tests, varying from 20 up to 120 ppm. Concentration of the Hydrocarbons and Carbon Monoxide in the exhaust gas characterizes the completeness of combustion process in the cylinder of an internal combustion engine and it is also an indicator of the engine workflow. Complete combustion results in the production of Carbon Dioxide and water. The incomplete combustion results in the Carbon Monoxide formation and soot (carbon).

*Complete combustion:*



*Incomplete combustion:*



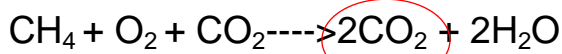
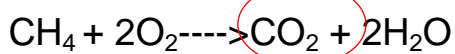
When unburned fuel is emitted from the engine, the emission could cause by fuel which didn't reach the flame zones or the methane could reach the flame zone but the residence time was too short. In addition, partial combustion of methane will also show UHC formation. Some regions of the combustion chamber may have a weaker flame. Fuel-air mixture may have

either fuel-lean or fuel-rich conditions and consequently have a lower combustion temperature.

Methane combustion emissions results of test #1 (see figure 27), performed at the 0.4kW load, are showing that the combustion was more incomplete than other tests, held at the same conditions.

Further experiment was done with addition of Carbon Dioxide to make simulated landfill gas.

The next set of tests was held at the following conditions: 400W load, 0% syngas, landfill gas combustion. The fact that simulated landfill gas consist 50% from Carbon Dioxide, make it expect to see more Carbon Dioxide in the emissions. Based on the stoichiometric reaction, twice more Carbon Dioxide should be emitted:



The averaged results from the experimental landfill gas combustion shows that Carbon Dioxide emissions increased slightly less than twice (see figure 28), from 4.1 to 7.2 %. It is less than expected from stoichiometry equation. However, stoichiometric reaction assumes complete combustion and in case of those sets of experiment we are dealing with not complete combustion. Because of that, some Carbon turned into Carbon Monoxide and Unburned Hydrocarbons and we see much more of them in the Landfill gas combustion emissions comparing to Methane combustion emissions.

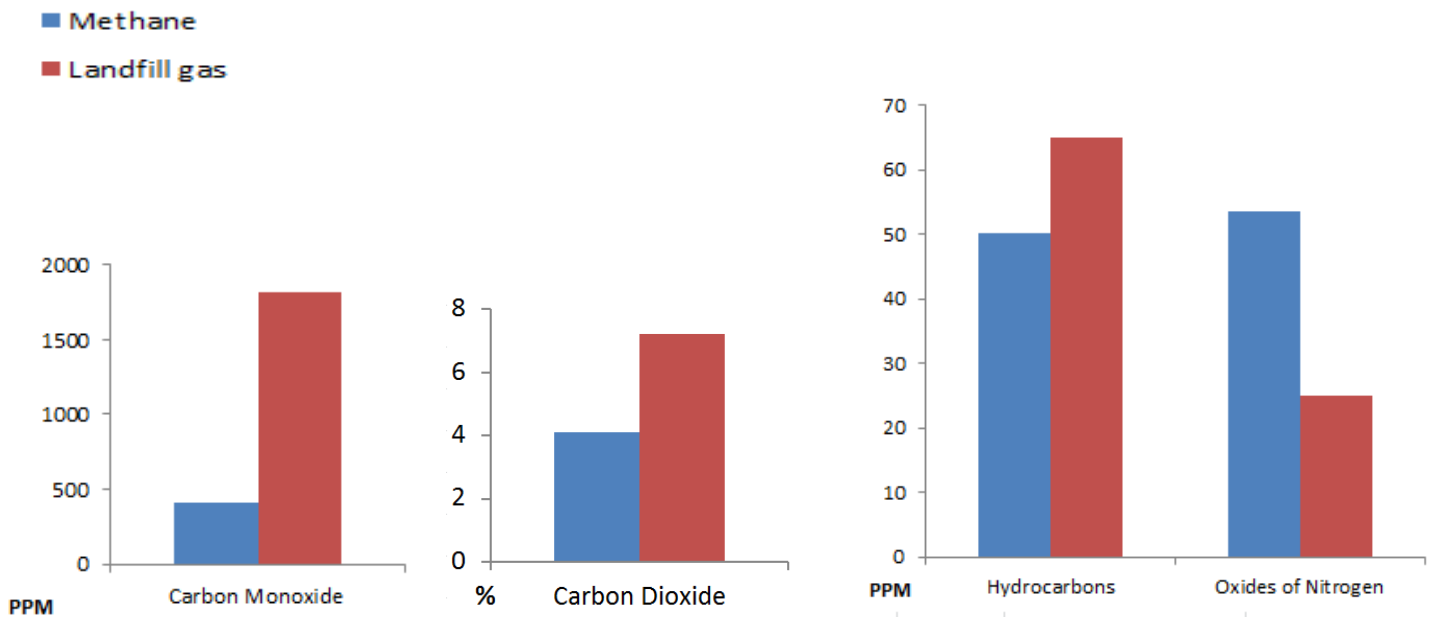


Figure 28. Comparison of Methane and Landfill gas combustion emissions

Observed increase of Carbon Monoxide was significant. Three times more Carbon Monoxide were emitted from Landfill gas comparing to Methane. Concentration of Unburned hydrocarbons increased by 29 % from 50 to 65 PPM.

Those results falls into the trend of previous research made on various mixtures of methane and Carbon Dioxide in IC engines. Canadian research of Prof Wong [17] conducted in 1977 examined potential of sewer gas combustion. Fuel mixtures containing up to 40% of CO<sub>2</sub> were investigated. It was found that when the fraction of Carbon Dioxide increased, unburned hydrocarbons and monoxide emissions were increased. Lowering the fuel quality tended to reduce Nitric Oxide emissions.

Assessment of simulated biogas as a fuel for the spark ignition engine by Huang and Crookes [16] from 1998 presents the same result for Nitric Oxide, saying that the main influence of Carbon Dioxide in the biogas fuel on engine operation was to lower the NO<sub>x</sub> emissions. That research shows that the CO emissions went up rapidly when the CO<sub>2</sub> fraction was increased above 30%. That can be caused by incomplete combustion. CO

emissions increased from 1.5% to 2.5%, almost 2 times, which is in line with current research - 3 times . When CO<sub>2</sub> was less than 30%, the CO emissions were low and did not change with the CO<sub>2</sub>. THC emissions increased from 500 to 680 PPM by 36 % while current research observe increase by 28% . NOx emissions decreased by 17% with higher fraction of Carbon Dioxide while current research shows 52% reductions.

In general , the trend that higher carbon dioxide fraction in a fuel leded higher concentration of unburned methane, thus CO and THC and reduces NOx due to lower flame temperature , falls in the line with previous research. More significant changes in increased emissions and NOx reduction could occur because of higher concentration of CO<sub>2</sub> in current research which was 50% while referenced research went only up to 40%.

Effect of Carbon Dioxide on the performance of biogas/diesel dual-fuel engine by Prof Bari [18] keeps the same trend of CO UHC and NOX emissions, pointing out that gas containing more than 40% carbon dioxide needs scrubbing, because it is found in this research that the engine ran harshly with biogas containing high carbon dioxide (>40%).

During the experiment, gas addition was made on the constant enthalpy base, which means that Carbon Dioxide did not replace part of the Methane in the mixture but was added at the same flow rate as methane. Despite of the fact that enthalpy of the fuel mixture stayed constant, Carbon Dioxide works as a diluent. It lowers the heating value of the mixture while doesn't react. That combustion stimulates the instability of the combustion process which leads to increasing emissions from the exhaust.

Syngas addition test was successfully done only ones, thus the data in Fig 29 is not an average through series of test but the results of that one test

and is not fully reliable. However, that test shows interesting result of significant emission reduction comparing to Landfill gas combustion.

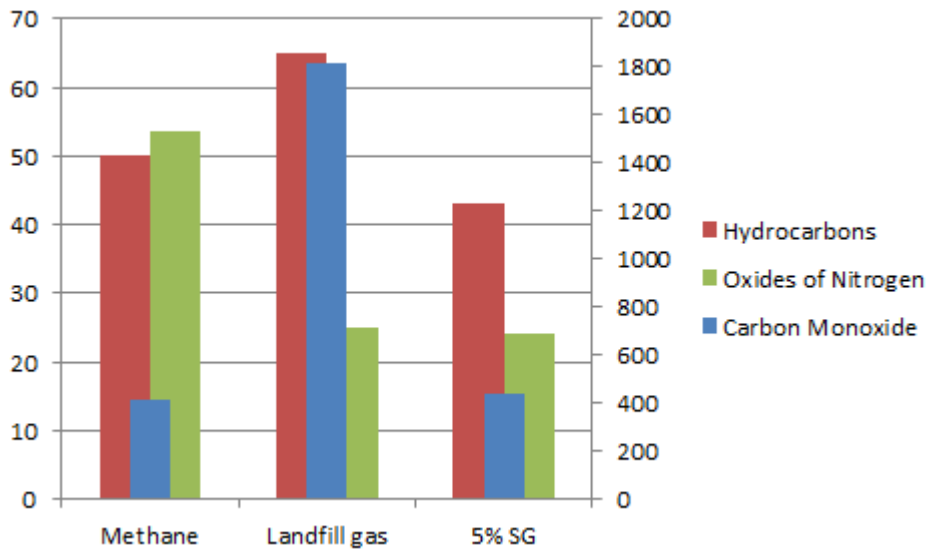


Figure 29. Comparison of Methane, Landfill gas and Syngas combustion emissions

Amount of hydrocarbons decreased by 33 %, Carbon Monoxide emitted 4 times less than from Landfill gas combustion, Oxides of Nitrogen slightly decreased by 4%. Syngas addition leads to better combustion. NOx was reduced with Syngas addition because it allows lean burn combustion to more cool combustion.

Performance of an Internal Combustion Engine Operating on Landfill Gas and the Effect of Syngas Addition by McKenzie [6] shows the same rate of CO reduction- from 802 to 214 PPM. However, emission reduction of UHC and NOx were achieved in much greater values than in current research: 89% reduction of UHC and 38% for NOx. In general, all emissions were decreased in both cases which prove that addition of syngas allows performing more stable combustion of fuel at lower temperatures.

Another parameter commonly used to evaluate the emissions based on fuel composition and load is a brake specific emissions. Brake specific fuel consumption (BSFC) is defined as the amount of fuel consumed for each unit of brake power per hour. It indicates the efficiency with which the

engine develops the power from fuel. Different BS characteristics can be used to compare performance of different engines in terms of efficiency or emissions.

BSNOX = Brake specific oxides of nitrogen emissions.

The ratio of the rate at which oxides of nitrogen leave the engine exhaust manifold to the brake horsepower. To compare tests results with EURO V<sup>1</sup>, NOx emissions for heavy duty vehicles have a limit set at 2g/kWh. (see table 4) It never reached that amount during the tests.

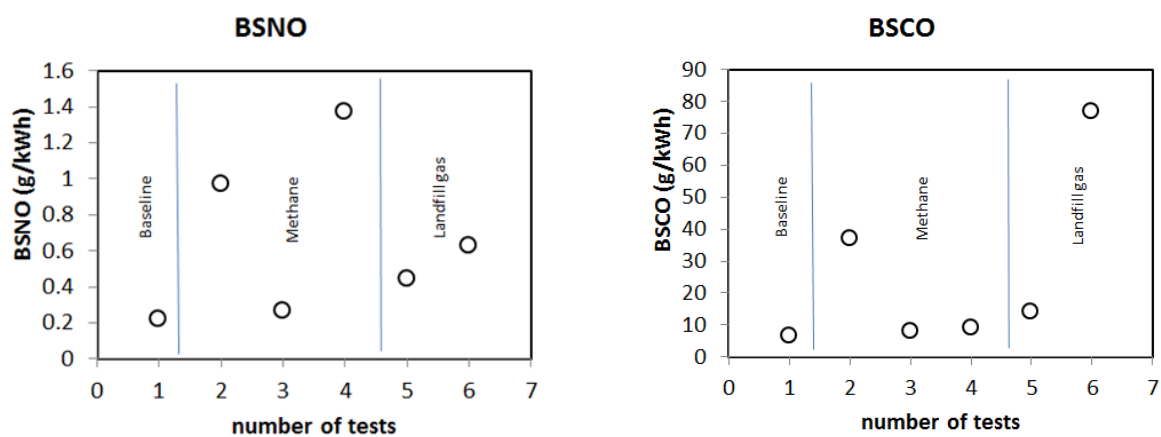


Figure 30. Brake specific values for oxides of nitrogen and carbon monoxide

BSCO = Brake specific carbon monoxide emissions.

The ratio of the rate at which carbon monoxide leaves the engine exhaust manifold to the brake horsepower. EURO V CO emissions for heavy duty vehicles have a limit set at 1.5g/kWh (see table4). None of the tests were able to meet that limit.

<sup>1</sup> European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. Currently, emissions of nitrogen oxides (NOx), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types, including cars, lorries, trains, tractors and similar machinery, barges, but excluding seagoing ships and aeroplanes. For each vehicle type, different standards apply. ([Wikipedia](https://en.wikipedia.org/wiki/Emission_standards))

BSHC = Brake specific hydrocarbon emissions.

The ratio of the rate at which hydrocarbons leave the engine exhaust manifold to the brake horsepower. EURO V HC emissions for heavy duty vehicles have a limit set at 0.46g/kWh. Only 2 test met the European limit, one of which is a baseline test.

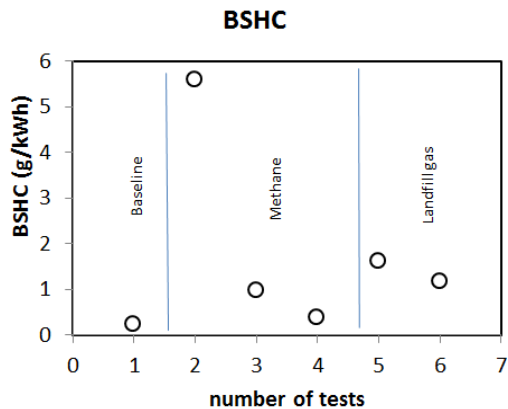


Figure 31. Brake specific values of hydrocarbon emissions

Test #2 shows poor results in both BS Carbon Monoxide and BS Hydrocarbon emissions, because incomplete combustion reaction took place during that test.

Table 4. Euro norm emissions

Standard	Date	CO (g/kWh)	NOx (g/kWh)	HC (g/kWh)	PM (g/kWh)
Euro I	1992–1995	4.9	9.0	1.23	0.40
Euro II	1995–1999	4.0	7.0	1.1	0.15
Euro III	1999–2005	2.1	5.0	0.66	0.1
Euro IV	2005–2008	1.5	3.5	0.46	0.02
Euro V	2008–2012	1.5	2.0	0.46	0.02

## II. 9 Conclusions and Further work

This work has shown that presence of Carbon Dioxide in the fuel mixture, so-called simulated landfill gas, deteriorated the engine performance and produced more pollutants in emissions than pure methane. At the same load conditions, engine efficiency was decreased by mixing with Carbon Dioxide. Syngas addition was proved by Jechan Lee in his Master Thesis [11] to be the most effective gas to reduce pollutant emissions out of Hydrogen and Carbon Monoxide .

Because of high laminar flame speed and low ignition energy of Hydrogen and fast burning rate of Carbon Monoxide, the addition of syngas to Landfill gas changes characteristics of combustion process, which results to increasing reactivity of the fuel mixture.

During this research the author could not implement all series of test. To make stronger arguments in favor of Syngas addition, further experiments are needed.

It is suggested to continue testing 5 and 10 and 15% of syngas additions at different loads to get a complete picture of the effect on emission and engine efficiency. It is important to vary the H<sub>2</sub> and CO ratio in the syngas, ideally landing on an optimal composition that can be produced by autothermal reforming. Due to diverse CH<sub>4</sub>/CO<sub>2</sub> ratios on different landfills it is critical to conduct the same tests with reduced amount of CH<sub>4</sub> to determine maximum feasible CO<sub>2</sub> concentration in landfill gas.

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28. "Ecological condition of landfills and waste dumps Moscow region, assessing their impact on the environment"

<http://www.solidwaste.ru/i/jurnaldocs/66/1-4.pdf>

## Appendix A:

Table 5. List of Equipment

Engine	Honda GC 160E-QHA
Generator	PRAMAC EG2800
Emission analyzer	ENERAC 700
Power meter	Wattsup Pro meter/ multimeter
Rotameters (4)	OMEGA FL1300/1400
Air Flow meter	OMEGA FMA 1700/1800
Methane cylinder	T.W. Smith Corp, ultra high purity 99,999%
Carbon Dioxide cylinder	T.W. Smith Corp, UHP
Hydrogen cylinder	T.W. Smith Corp, UHP
Carbon Monoxide Cylinder	T.W. Smith Corp,UHP
Surge tank	
pressure gauges (7)	
check valves (2)	Air and fuel lines before surge tank
needle valves (2)	Extra air and air flow meter
Quarter turn valves (5)	To each gases and final mixture
On off valves (2)	For emergency exhaust
Fittings	
Stand	To hold emission analyzer probe
tubing 1/4 inch	
tubing 3/4 inch	

## Appendix B

Table 6. TRR issues and solutions outline

ISSUE	SOLUTION TO BE IMPLEMENTED	COMPLETED
Kink in the tubing from the CO <sub>2</sub> cylinder	Insert a length of ss tubing connecting to cylinder so that plastic tubing will be less likely to kink	done
What is the delivery pressure of house air?	Put a pressure gauge between house air and mass flow meter	complete
What is the pressure rating of the check valves?	Look up specifications on Swagelock	The check valves have a cracking pressure of 1 psi and a room temp pressure rating of 2200 psig
There is small leak by pressure gauge downstream of mass flow meter	It is tightened as much as possible so Teflon tape is needed	Yes, no longer leaking
What can be max pressure in the fuel line	Find pressure ratings of all tubing used	From McMaster: PTFE semi-clear white 3/8" w/1/16" wall—150psi; 1/4" w/1/32" wall—130psi. <i>However</i> , fuel line is clear(er) and it is not certain it has same rating as semi-clear. (no clear tubing on mcmaster)
Possible leaks from unused fuel inlet ports	Cap them	Yes
Plastic tubing on pressure gauge downstream of fuels	Replace with ss tubing and ensure that gauge is visible during operation	done
In case of emergency shut-off, there needs to be a way to depressurize both the fuel line and the surge tank	Add another vent valve between the on/off and the surge tank. When in off position, each section can be depressurized separately	Yes
How will we take enerac measurements? Avoid reaching across hot engine	Use a stand and clamp to hold the enerac probe while engine is in operation	ok
Live connections on the load board	Cover with electrical tape. Also, need to have a better understanding of how to take power measurement	Put generous amount of electric tape

Positioning of load board—not ideal	Would ideally like to hang on wall, but not really possible with current configuration. Just make sure it is accessible, but not in the way. May need an extension cord	Will stand to the left of the fume hood
Gas detectors—currently have in the lab for CO and CH <sub>4</sub> , but will later use H <sub>2</sub> and will need one for that	Research gas detectors.	Ordered multiple gas detector (H <sub>2</sub> , CO, CH <sub>4</sub> ) June 30

## Appendix C

Within the scope of the research, the group visit to the Fresh Kills landfill was conducted. The landfill was opened in 1947 as a temporary landfill, but eventually became New York City's principal landfill and was once the largest landfill, as well as human-made structure, in the world. The landfill was closed in 2009 for redevelopment.



## Appendix D. Review of waste management in Russia and in Moscow

Research sponsored by Global WTER Council and National Science Foundation

### Introduction, Russia

Russia is geographically the largest country in the world and also a major pollutant. Russia wants to be considered as part of Europe and to be integrated in world events, such as international expositions, the Olympic Games, etc. Sustainable development is one of the most discussed topics for the last 30 years, but there is no national directive as to how to manage the generated municipal solid wastes (MSW) in the country.

The potential for applying better waste management systems in Russia is huge. As part of Soviet heritage, Russia has a strong industrial base and a fairly good academic system but, in contrast to northern Europe, still landfills most of its waste and substantial improvements could be made in the capital region and other big cities of this country.

### MSW generation in Russia

The latest governmental report [22] states that in 2011 52.3 million metric tonnes of Municipal Solid Wastes (MSW) were generated in Russia. The current disposition of MSW is shown in Figure 1 that shows 4% recycled, 1% combusted in waste-to-energy (WTE) plants and 96% landfilled.

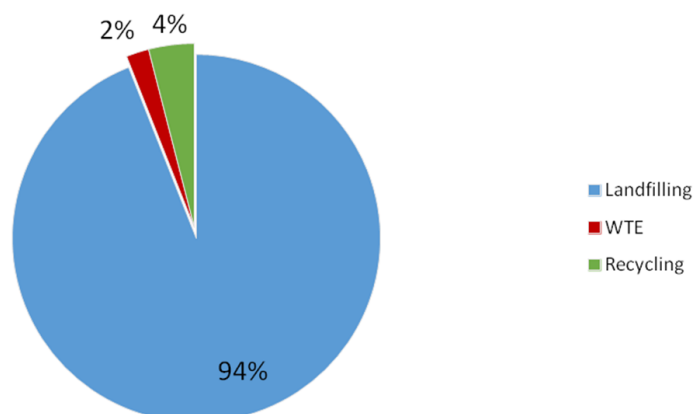


Figure 32. Disposition of MSW in Russia, 2011

The 2011 population of Russia was 143 million [27]; therefore, the per capita generation was 0.37 tonnes. This rate is in the range of countries such as Turkey, Serbia, and others (Figure 33).

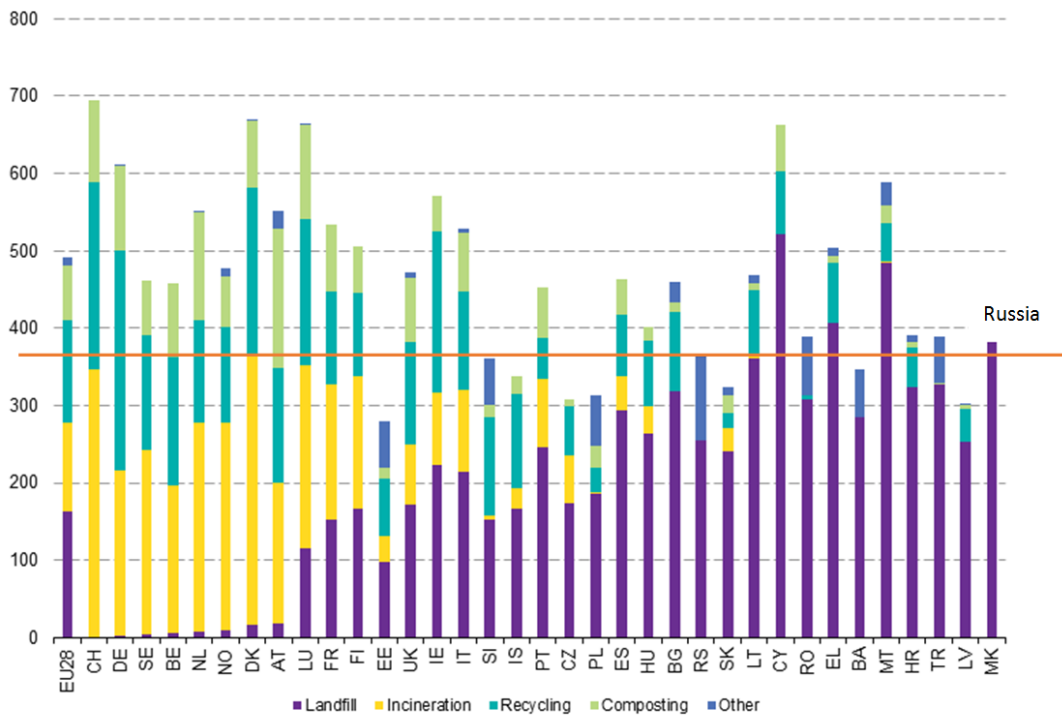


Figure 33. Per capita generation and disposition of MSW in Europe (nations are sorted from lowest to highest percent of MSW landfilled). Source: Eurostat, 2012

### Waste management in Moscow

According to the 2010 data [26], the capital has a population of 11.6 million and generated 5.9 million tonnes of municipal solid waste, corresponding to 518 kg of MSW per capita. Collection of MSW in Moscow is managed by the Governmental Unitary Enterprise “EkoTechProm”. Of this amount, an estimated 530,000 tonnes (9.6%) were recycled, 765,000 tonnes (13.9%) combusted with energy recovery, and 4.2 million tonnes (76.4%) were landfilled (Figure 34).

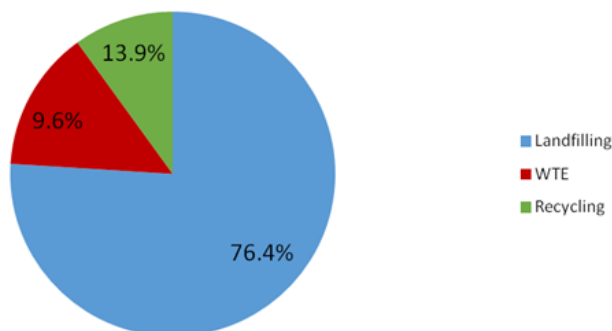


Figure 34. Disposition of MSW in Moscow

## Recycling in Moscow

The official city report [26] states that 9.7% of the city's MSW was recycled. Recycling is mainly concentrated on packaging materials. High rates, comparable to European rates, are achieved with some types of wastes such as paper, cardboard and glass. The recycling rate of some packaging materials is up to 30%, which is close to the Packaging Waste Directive of the European Union (94/62/UN)[3]. However, the rate of recycling is lower than the Directive, when one considers each type of packaging materials separately.

There are a few private composting facilities in the Moscow area but the contribution of composting is negligible in terms of the total amount of generated wastes.

## Waste-to-energy (WTE)

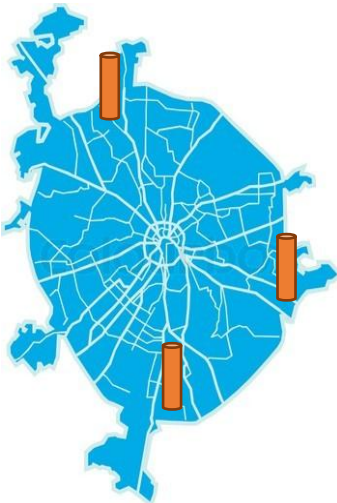


Figure 35. Location of WTE plants in Moscow

There are three waste-to-energy (WTE) plants in Moscow, out of a total of seven in Russia. The locations of these facilities are shown in Figure 35. Two of these plants are operated by the governmental company “EcoTechProm” and have a capacity of 130,000 and 275,000 metric tons per year, respectively. The third one is operated by the Austrian company EVN-Group and has a capacity of 360,000 tons per year. In total, the three WTE plants process 765,000 metric tons of MSW, i.e., 13.9 % of the total generation [25]. Figure 36 shows the tonnage processed in the three WTE plants of Moscow in the period from 2004.

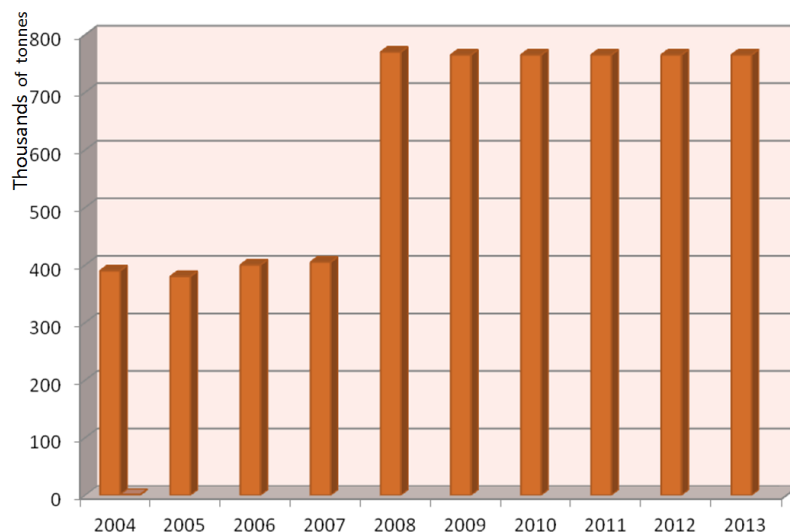


Figure 36. MSW combusted in Moscow WTE plants

Waste to energy in Russia started during the Soviet Union period in 1975, when the first plant for thermal treatment of municipal solid wastes opened with two lines of 72,000 tonnes capacity each. Electrostatic precipitators were used in the Air Pollution Control system of the plant. As part of the Moscow sanitation program of 1992, it was decided to retrofit this plant. It was opened again in 1995 with an additional line and significant gas cleaning improvements.

The EVN Group is an Austrian-based producer and transmitter of electricity. It is one of the largest in Europe with over three million customers in 14 countries. The company also operates in wastewater treatment, natural gas supply and waste management business facilities. It is the second-largest utility in Austria. In Moscow, the EVN Group operates WTE plant #3 of which it owns 70%; the other 30% belongs to EcoTechProm.

There is another WTE plant in Moscow which is based on fluidized bed technology. However, the plant did not allow the author to visit and does not post any data online. However, it is known that in addition to municipal waste combustion the plant recycles PET-bottles. Processing is located in the main building of the plant. The mode of operation is 12 hours a day and the annual capacity is 8000 tons.. Feedstock - selected from municipal solid waste (MSW) PET bottles. The recycled product is PET flakes (chips) with a size of 10-20 mm, while ensuring the impurities to be less than 0.012% and humidity 0.5% [25].

Table 7 summarizes the known data for the all three WTE plants of Moscow.

Table 7. Comparison of WTE plants in Moscow

	WTE Plant#2	WTE Plant#3	WTE Plant#4
Location	Otradnoe	Birulevo	Rudnevo
Company	EcoTechProm	EVN	EcoTechProm
	1975 as a 1 <sup>st</sup> Russian WTE plant.  Retrofitted in 1995	2007	2003
Capacity tons/year	130,000	360,000	275,000

Lines	3	2	3
Boiler technology	Moving grate	Moving grate	fluidized bed
Fuel heat output		92 MW	Before burning, waste is sorted and separated recyclables and non-combustible materials, including paper, cardboard, plastic, glass, ferrous and non-ferrous metal, large fraction of waste is crushed. PET packaging capacity of 8000 tons per year
Av Calorific value, MJ/kg	7.9	7.5	
Flue gas cleaning technology	Activated carbon, lime milk, 726 baghouses	Spray absorber Fabric filter DeNOx plant	
Heat generation	for internal needs	370 000Gcal/year	
Electricity generation, MWhr/year	19 470 50% for the internal needs	38 000	
Price for 1 tone, \$	79	55	78

*Source: interview and visit by author of plants #2 and #3.*

### Landfilling

It is reported [22] that 2.3 million metric tons of MSW were disposed at sanitary landfills in the Moscow Oblast, which corresponds to 41.8% of the total MSW generated. The rest 34% of the total wastes were dumped, see Figure 37. Moscow Oblast is the second most populous federal region of Russia, located around the borders of Moscow City. According to Federal regulations, landfilling within Moscow City is prohibited and all city waste goes to the Moscow Oblast landfill. The Ministry of Natural Resources and Ecology reported [22] that another 1.4 million tonnes were handled by private companies under direct contracts with other landfills and waste dumpsites in the Moscow Oblast; 0.5 million tonnes were disposed at non-regulated landfills and dumps in the Moscow Oblast under direct contracts with housing and communal services. As noted earlier, in total 76.4 % of the Moscow MSW is disposed in all types of landfills.

One of the reasons why the majority of wastes are going to landfills is the cost of disposal. In comparison to the gate fees at the WTE plants (Table 7), the

landfill fee is only \$8.6/tonne. Even though the landfill gate fee is very low, waste dumping costs less, resulting into one third of all generated MSW to be disposed in non-regulated waste dumps.

Russian landfills receive all types of waste because sorting and separation services in Russia are not common. As a result, MSW is mixed with hazardous, industrial, medical and construction waste, causing a huge negative impact on the environment, mainly air, soil and water pollution. The treatment of industrial, hazardous and construction waste types will only become profitable once sorting and separation is more adopted by businesses, as well as by the public. [24]

Because of the mixture of waste types, landfills often are subject to spontaneous combustion. For example, on August 19, 2010, at a suburban 15-hectare landfill near Moscow, approximately 20 fire engines were used to extinguish a spontaneous fire that had been smoldering for days prior to the outbreak. Some years back, a landfill fire at the old Thessaloniki landfill (Tagarades, Greece) was estimated to have emitted about 200 grams of toxic equivalent dioxins (grams TEQ); for comparison, the entire U.S. WTE industry in 2012 emitted less than 5 grams TEQ (reference to Henri Dwyer thesis)

The Moscow Oblast has 59 authorized landfills [28], and probably a similar number of unauthorized waste disposal sites. The 2010 landfill fire raised public concern regarding air pollution and monitoring landfill sanitary norms.

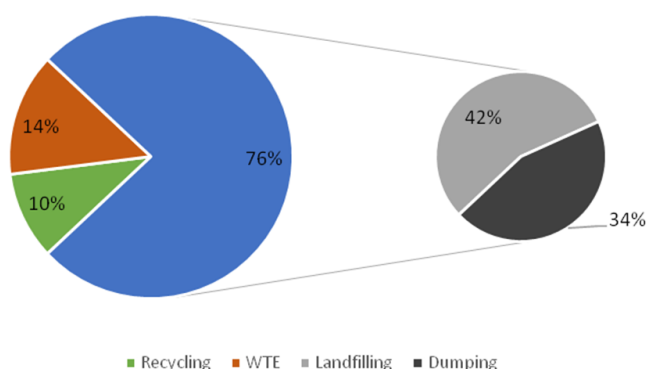


Figure 37. MSW management in Moscow

## MSW generation in the Russian “megacities”

“Megacities”, according to the Russian Federation, are cities where the population within the city borders is more than 1 million. Figure 38 shows the population and MSW generation of 10 Russian “megacities”.

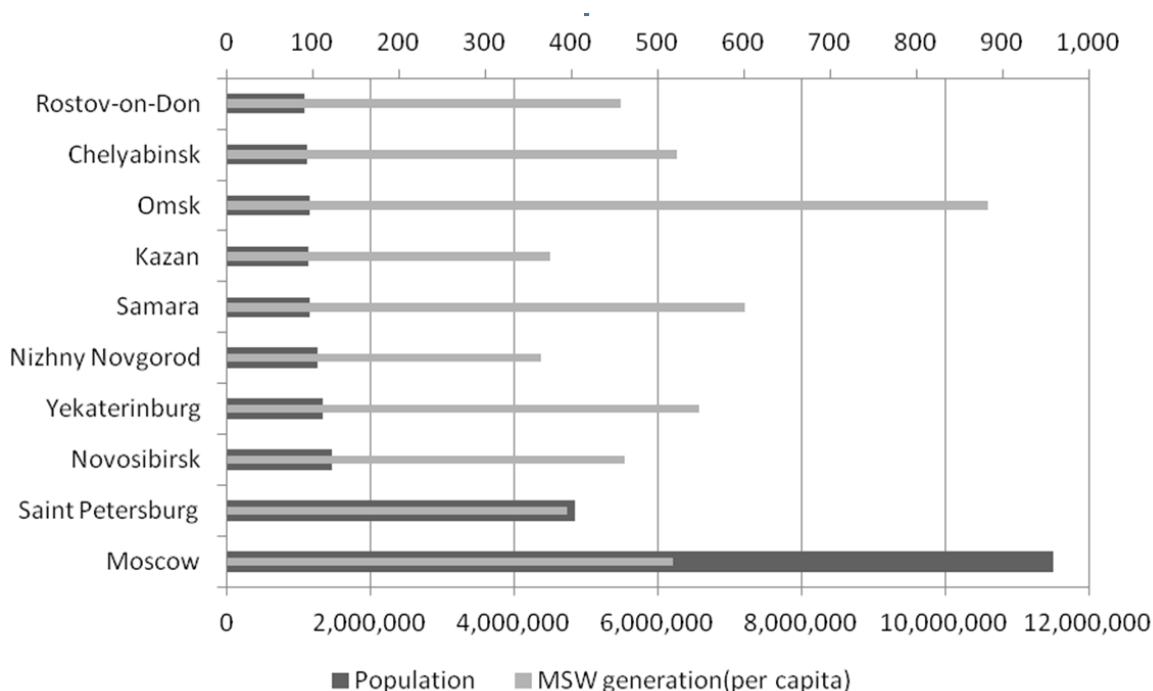


Figure 38. Russian Megacities MSW generation. Research by the author for D-waste Atlas (<http://www.atlas.d-waste.com/2014-report>)

The composition of MSW of the Russian cities is not the same, as shown in Figure 39. However, it is possible to see some trends: Organic waste is the major component in all cities, except Kazan. Second place is held by paper and cardboard. The composition of plastics is always 10% of total and metal is usually less than 5% out of total.

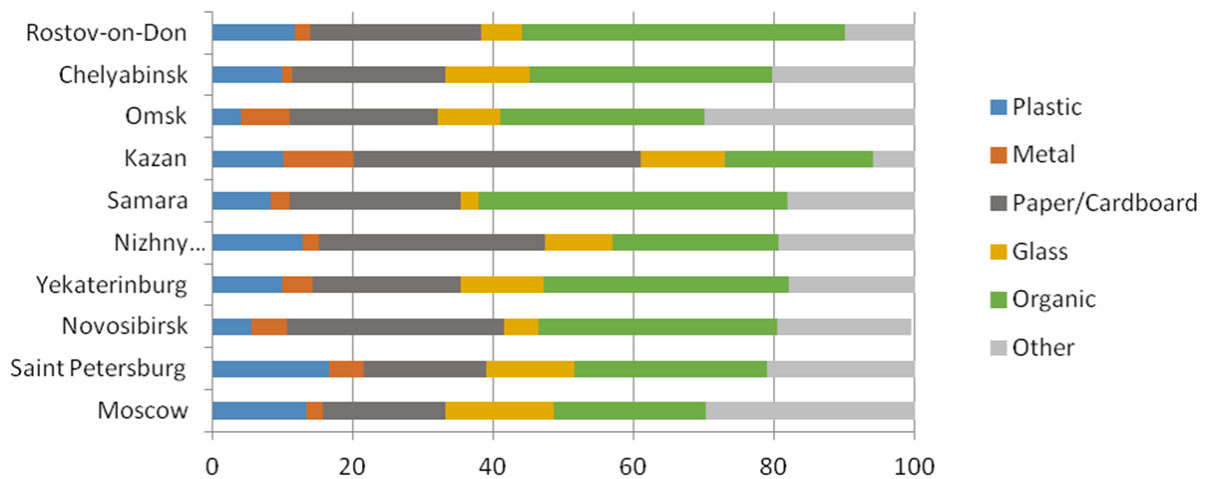


Figure 39. MSW composition of ten Russian Megacities

## Discussion

Russia has undergone significant changes since the collapse of the Soviet Union, moving from a globally-isolated, centrally-planned economy towards a more market-based and globally-integrated economy, but stalling as a partially reformed, statist economy with a high concentration of wealth in officials' hands. Economic reforms in the 1990s privatized most industry, with notable exceptions in the energy and defense-related sectors [23]. Waste treatment companies remind to be monopoly and owned by government. As for today, Russia is 7<sup>th</sup> economy in the world [23], however, the infrastructural lag, across all industries and sectors, is an intense problem for the federal government and society. The waste management sector is in dire need of restructuring and opening up to market forces.

Municipal solid waste management system is one of the key components of a country's overall environmental and resource efficiency framework. Inefficient MSW management in Russia today is causing negative environmental impact and results in suboptimal use of raw materials and energy.

However, there are a lot of opportunities for waste management development in the country. Incorporation of Russia into the European society and in international organizations can lead to increasing demand of sustainable solutions for Waste Management.

For densely populated megapolis as Moscow, recycling and waste to energy are absolutely essential for sustainable development, conserving land by avoiding landfilling, providing electricity and heat, and reducing greenhouse gas emissions.