PROJECT TITLE: Thermal Conversion at the Brooklyn Navy Yard: A Proposal for Small-Scale Waste to Energy Gasification

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Abstract

The Brooklyn Navy Yard (BNY) is a mixed-industrial campus located along the East River in northwest Brooklyn, New York. The diverse businesses at BNY work in industries including shipbuilding, filmmaking, woodworking, architectural design, modular housing construction, and many more. The Brooklyn Navy Yard Cogeneration (BNY Cogen) facility provides electricity and district steam heating to BNY, as well as to sell to Con Edison (ConEd). BNY Cogen uses natural gas in a Siemens Combined Cycle process to generate 286 MW of thermal and electrical power. The aim of this project is to design a waste to energy (WtE) process for BNY. The solution will utilize the garbage generated during BNY daily operations as a feedstock in a small-scale thermal conversion facility. The "producer gas" produced will be available for use by BNY Cogen to augment their natural gas supply. The garbage used to power the WtE facility will not need to be collected by waste carting companies, saving BNY tenants money and keeping the garbage out of landfills. Ultimately the goals of the BNY WtE system are to save money, save resources, reduce waste, reduce trucking, and reduce greenhouse gas (GHG) emissions. A successful plan and implementation of WtE technology at BNY could serve as an example for similarly scaled industrial parks and campuses nationwide.

Key Words: waste to energy, WtE, energy from waste, gasification, MSW, zero waste, OneNYC, Brooklyn Navy Yard, sustainability, landfill diversion, thermal treatment

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Acronyms and Abbreviations

BNY	Brooklyn Navy Yard
BNYDC	Brooklyn Navy Yard Development Corporation
BNY Cogen	Brooklyn Navy Yard Cogeneration Facility
CAA	Clean Air Act
CCNY	City College of New York
C&D	construction & demolition (waste)
CHP	combined heat and power
ConEd	Consolidated Edison
CUNY	City University of New York
DEC	New York State Department of Environmental Conservation
DEP	New York City Department of Environmental Protection
DSNY	New York City Department of Sanitation
EfW	energy from waste (synonymous with waste to energy)
EPA	Environmental Protection Agency
EU	European Union
GHG	greenhouse gas
HHV	higher heating value
LHV	lower heating value
LSHT	low speed high torque
MACT	maximum achievable control technology
MORR	Mayor's Office of Recovery and Resiliency
MOS	Mayor's Office of Sustainability
MSW	municipal solid waste
NYC	New York City
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
O&M	operations and maintenance
ppm	parts per million
PTC	Production Tax Credit
QECB	Federal Qualified Energy Conservation Bonds
SMWC	small municipal waste combustors
SWMP	Solid Waste Management Plan
tpd	tons per day
U.S.	United States
WtE	waste to energy (synonymous with energy from waste)
Yard	Brooklyn Navy Yard

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1. Introduction

In New York City (NYC), as in the United States (U.S.) as a whole, the most prevalent method of trash disposal is landfilling. As the population grows, more space to contain waste is required; the cost of landfilling is simultaneously increasing. GHGs from waste transportation to landfills and storage within the landfills are a major problem. Many municipalities are moving away from landfilling toward more sustainable, more local, multi-faceted solutions. Increasing the recycling rate, decreasing the packaging in consumer products, and reusing materials are crucial actions for creating a long-term sustainable waste management plan. For the materials which are not recyclable, waste to energy (WtE) is an underutilized and potentially environmentally beneficial alternative to sending waste to landfills.

This project explores WtE as a solution to multiple problems at an industrial park called the Brooklyn Navy Yard (BNY). The diverse businesses at the BNY generate approximately 30 tons per day (tpd) of mixed refuse, a combination of municipal solid waste (MSW) and construction and demolition (C&D) waste. Private carting companies drive through the surrounding neighborhoods to take the waste to transfer stations and onward, resulting in noise and emissions. The onsite electricity and steam power plant, the BNY Cogen facility, uses natural gas as its fuel and has historically been overpaying for fuel.

Through exploration of the BNY, estimation of its waste stream, familiarization with the needs of the cogeneration plant, and discussions with various professionals including the former Vice President (VP) of Maintenance at the Brooklyn Navy Yard Development Corporation (BNYDC), the Projects General Manager at Power Plant Management Services, LLC (which operates the BNY Cogen plant), a Senior Engineer from New York City's major power provider ConEd, as well as representatives from various equipment manufacturers, the project team has developed a detailed WtE scheme for the BNY utilizing thermal conversion gasification technology. Energy calculations, a cost/benefit analysis, and funding mechanism possibilities are presented in this report. This idea, using on-site waste to create a gas to contribute to an existing power generation facility while reducing waste transportation and landfill-associated emissions, may also transfer to other industrial parks and campuses.

2. Waste Overview: United States and New York City

The U.S. has a waste problem. At a national level, the U.S. produces ⅓ of the world's waste but has less than 5% of the global population (GrowNYC, 2015). At an individual level, an American generates over 50% more waste per day – nearly 4.5 pounds versus less than 3 pounds – as compared to an inhabitant of the EU-27 countries as of 2013 (EPA, 2015; Eurostat, 2013). The good news is that in the U.S. the average amount of waste generated per person has been decreasing slightly over the past fifteen years **(see Figure 1)**. However, while per capita waste generation is decreasing, total waste generation is increasing. Due to population growth the decrease per person is not significant enough to counteract the total increase in MSW generation.

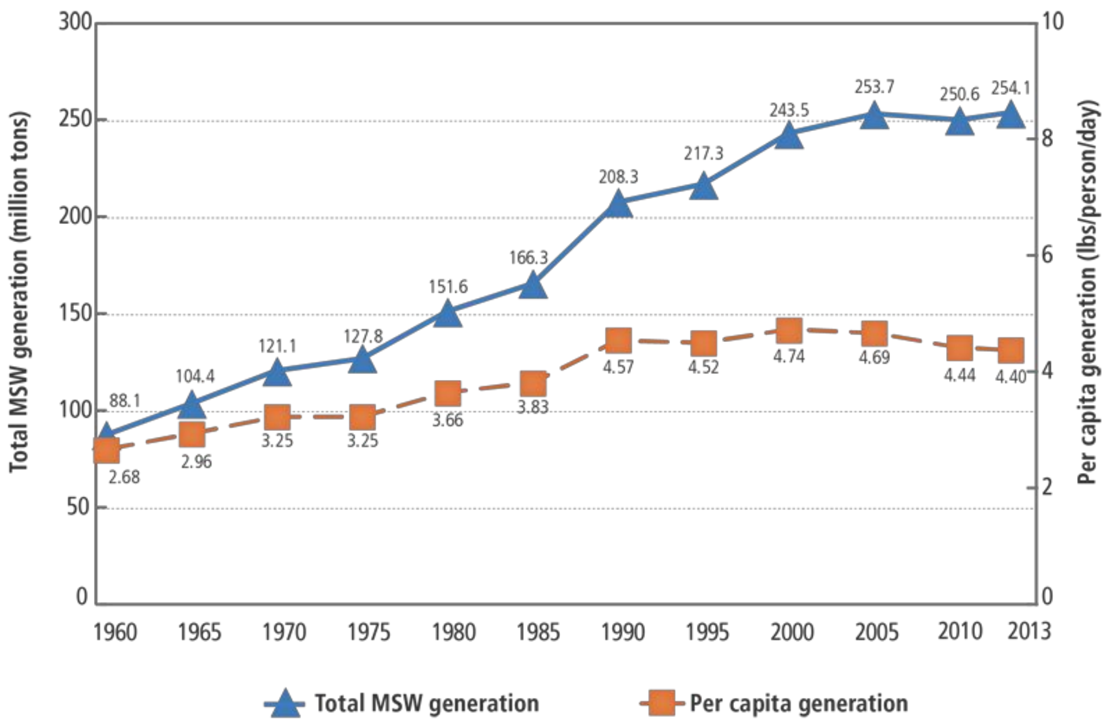

Figure 1: MSW Generation Rates, 1960-2013 (Source: EPA, 2015)

Where does all this waste go? According to the EPA (2015), in the U.S. we send more than half of our MSW to landfills with many regions sending more than three quarters of their total MSW to landfills **(see Figure 2)**. Although some cities are making efforts to decrease their amount of MSW that is disposed of in landfills, the EPA has yet to set an aggressive national target that could serve as a guiding light for planners of waste management policy throughout the country. (New York City's *OneNYC* zero waste goal is covered in the next section.) In comparison, the *European Commission's Landfill Directive 1999//31/EC* was recently updated with a target maximum landfill rate of 25% by 2025 (European Commission, 2015). Although the U.S. is not as limited in land as are many European countries, there are numerous other environmental issues that warrant the implementation of alternative disposal methods. Landfills are responsible for a significant amount of GHGs, a major contributor to climate change. The two primary GHGs emitted in relation to the process of landfilling are carbon dioxide (CO_2) and methane (CH_4). Methane is released during decomposition and is more than 25 times as potent as CO_2 (Anderson et al. 2010). In 2011, landfills generated 17.5% of all human-generated methane in the U.S. (LMOP, 2013). Additionally, many cities transport their waste great distances to landfills in other states further adding to GHG emissions from trucking related CO_2 emissions.

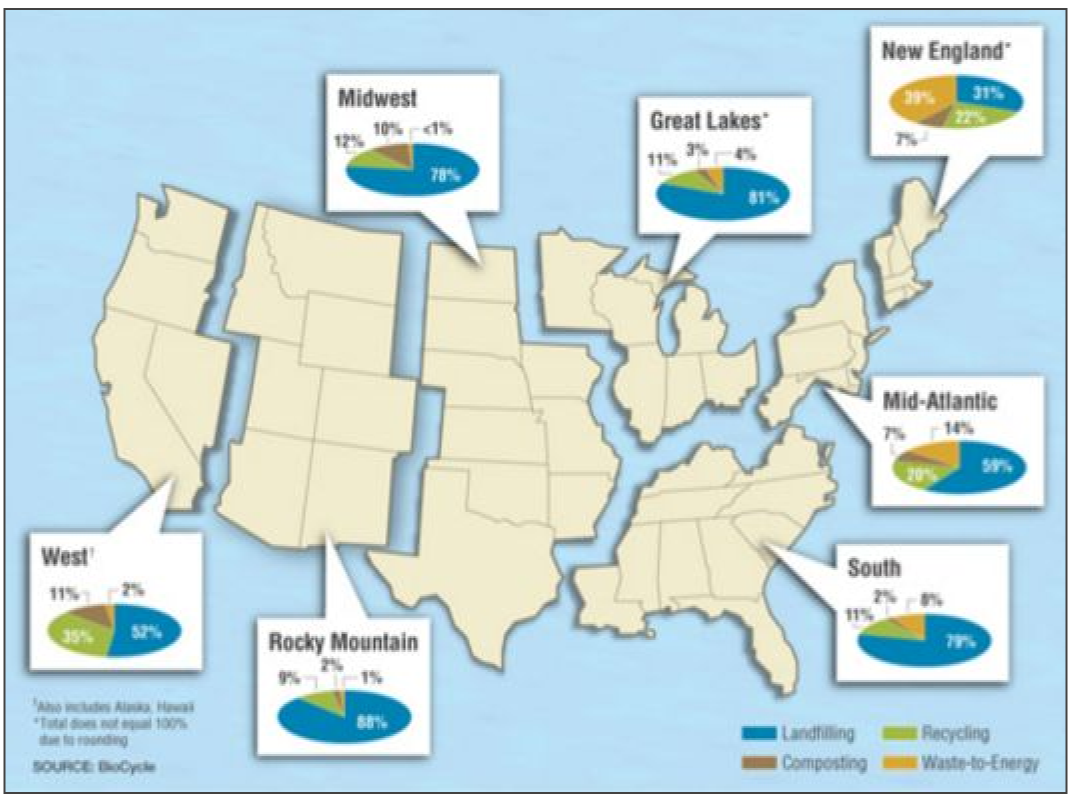

Figure 2: Disposal of MSW in the United States by Region, 2008
(Source: Biocycle & The Earth Engineering Center of Columbia University, 2010)

As is the standard practice with the rest of the country, NYC relies heavily on landfill disposal as well. As a city, we produce over 14 million tons of waste and recyclables per year, for residential alone (MORR, 2015). The New York City Department of Sanitation (DSNY) is responsible for collecting over 4 million tons of that total – primarily from residential outlets – sending 68% of it to landfills, mostly in Pennsylvania, Virginia, and New Jersey. A much smaller portion is processed through comparatively more sustainable methods: less than ⅕ (17%) goes to WtE facilities in the region and ⅙ (15%) is recycled **(see Figure 3)**. In order increase the landfill diversion rate, the WtE and recycling portions need to increase. In order for that to happen, advancements in policy, regulation and education are required. In the mid-1930's the Atlantic was a dumping ground for NYC until it was legally prohibited. It took the passing of a New Jersey Court Order which then had to be upheld by the U.S. Supreme Court in order to legally prevent people from disposing of trash in the Atlantic ocean (ASTCI, 1998). See **Table 1** for a more complete timeline of NYC waste disposal milestones.

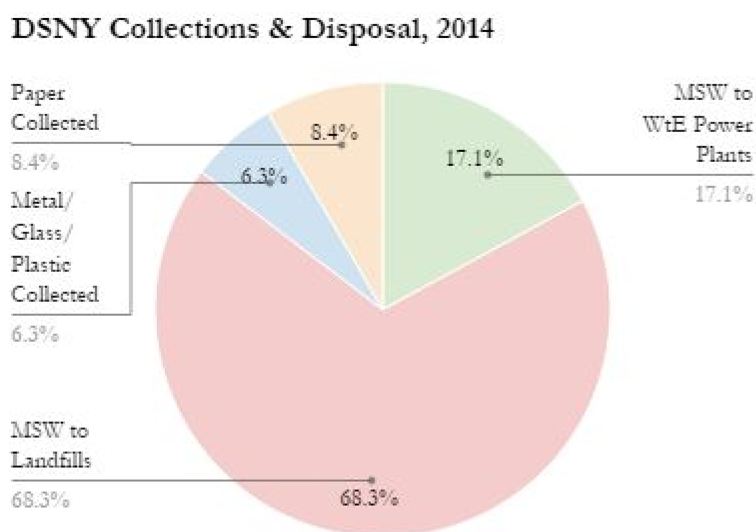

Figure 3: DSNY Collections and Disposal, 2014
(Source: Compiled by the authors using data from the Deputy Director of Solid Waste Management, DSNY, 2015)

Year	Milestone
1934	Ban on dumping of MSW in the Atlantic ocean in NYC
1947	Fresh Kills landfill opens on Staten Island, proposed by Robert Moses as temporary solution
1970	Federal Resource Recovery Act amends the Solid Waste Disposal Act, emphasizing recycling and reuse over disposal
1970	Federal Clean Air act enacted, prompting shutdowns of incinerators for failure to meet new emission guidelines
1982	NYS Returnable Container Law enacted (aka the Bottle Bill)
1989	NYC Local Law 19 passed, making recycling mandatory
1992	Solid Waste Management Plan (SWMP) from DSNY calls for extension of NYC curbside recycling, construction of a state-of-the-art incinerator at Brooklyn Navy Yard, and a rehabilitation and upgrade of the Southwest Brooklyn incinerator
1994	NYC's last municipal incinerator closes
1996	Under Mayor Giuliani, decision to close Fresh Kills announced, plus a ban on new landfills and incinerators in NYC; at that time, the city produced 13,000 tons/day, non-commercial waste
1996	Amendment to (1992) Solid Waste Management Plan (SWMP) from DSNY, calls for further expansion of NYC recycling program, and a more extensive environmental review of the Brooklyn Navy Yard and Southwest Brooklyn incinerators
2000	Modifications to 1992 SWMP from DSNY, focuses on waste exportation as a permanent solution
2001	Last barge of MSW sent to Fresh Kills in March 2001
2006	NYC adopts long-term SWMP with focus on improving disposal methods and spreading the burden more equally throughout the city
2007	*PlaNYC* from Mayor Bloomberg sets goal to increase diversion from landfills by 75% by 2030
2013	NYC Local Law 77 passed for DSNY 2-year Pilot Organics Collection Program, participation is voluntary
2013	NYC and Covanta Holding Corp. sign 20-year WtE agreement to take effect in 2015 for Covanta to convert approximately 800,000 tons per year MSW into electricity
2015	Expansion of NYC Organics Collection Program to serve approximately 135,000 households
2015	*OneNYC* from Mayor Bill de Blasio sets goal of achieving zero waste to landfills by 2030
2016	NYC's next SWMP due

Table 1: Timeline of NYC Waste Disposal Milestones

(Source: Compiled by the authors using data from multiple sources: DSNY, 2006 & 2015; Guo, 2013; Manevich, 2013; Themelis, Cohen, & Frankel, 2001)

After it became illegal to dump waste into the ocean, a new method was necessary to dispose of the city's waste. When Fresh Kills landfill was opened on Staten Island in 1947 for NYC's waste, it was planned as a temporary solution by the legendary and often controversial planner Robert Moses. However, the landfill stayed open for more than 50 years, receiving the last barge of NYC waste in 2001, under Mayor Giuliani's administration, when it was receiving 13,000 tons of waste per day and ranked as the world's largest landfill (Themelis, Cohen, & Frankel, 2001). If the long life of the landfill had been part of the original plan in the late 1940's then the project likely would have seen much more opposition from the community. They had originally expected only a few months or years of waste, and instead ended up with over five decades of waste and related emissions.

The NYC Solid Waste Management Plan (SWMP) was created in in 1992 to establish a waste plan for the city and to explore waste disposal initiatives including curbside recycling and a proposed incinerator at the BNY (Themelis et al., 2001). After the closure of the Fresh Kills landfill in 2001, NYC became a waste exporter, sending waste via transfer stations mostly by truck and rail to other cities and states. A 2014 *New York Environment* report outlines how the burden of waste processing is not shared equally throughout the city. Of the 58 waste transfer stations in NYC, over half (32) are located in the South Bronx and transfer over 60% of the city's waste (Crean, 2014). In 2006, under Mayor Bloomberg, the SWMP was updated to explore more sustainable waste disposal methods based on a 20-year timeline (2006-2025) and to more equally spread the burden of waste transfer and processing throughout the city (Hu, 2006). Specifically the report concludes that gasification technologies "merit further consideration by the City" (DSNY, 2006). Only one year later, in 2007, Bloomberg set the goal in his administration's *PlaNYC* to increase diversion from landfills by 75% by the year 2030 (Office of the Mayor, 2013). To work towards achieving that goal, NYC *Local Law 77* was passed in 2013 for the DSNY to implement a 2-year *Pilot Organics Collection Program* with voluntary participation. Additionally, NYC signed a 20-yr deal in 2013 (effective in 2015) to send an estimated 800,000 tons per year to a Covanta WtE facility in New Jersey (Goossens, 2013). For over twenty years the city has been exploring and experimenting with better ways to handle its waste.

After Mayor de Blasio took office in 2014 he set an ambitious goal in his *OneNYC* plan of zero waste to landfills by 2030. To achieve that goal he expanded the organics collection program to serve well over 100,000 households and nearly 40% of all Department of Education schools.

(DSNY, 2015). The pilot program is allowing the DSNY to collect data on the characterization of the organic waste stream so that they and partner organizations can refine their operations to more efficiently process it. Considering that the average American's waste stream is roughly 1/3 food waste, collection of organic waste can potentially offset a significant portion of the negative impact of landfills. For the remaining portion of the waste stream that is not suitable for recycling or organics collection, thermal WtE is an increasingly viable and sustainable alternative to landfill disposal.

A 2012 report on WtE facilities in NYC predicts that when the SWMP is updated in 2016 they will possibly change their prior stance in opposition to a commercial WtE facility in the city (Rizzo & Plumb, 2012). This would align with the conclusion in the 2006 report that gasification should be looked into for applicability in NYC. The City's waste legislation needs to be updated to accommodate the increase in total waste generation, as well as to counteract the effects of GHG emissions related to landfills. The quantity of waste that is being produced and the rate at which it is being produced are too large for natural systems to safely and sustainably digest it. Our focus in this paper is on WtE as part of the solution in reducing the negative impacts associated with landfills and achieving NYC's goal of zero waste to landfills by 2030. Although there are not any set plans that we're aware of to develop a thermal WtE facility in NYC in the near future, it appears that the political climate is slowly adapting to the idea.

3. *OneNYC* Overview

In 2007 under Mayor Bloomberg, NYC implemented its first sustainability plan – *PlaNYC* – to address the issues associated with an expected population growth to 9 million residents by 2040 (Office of the Mayor, 2015). One of the plan's key goals was to achieve a 75% landfill diversion rate by 2030. Initiative 8 of the plan – "Pilot conversion technologies" – mentions the prevalence of conversion technologies outside of the U.S. and recommends thermal processing as one of the methods that should be pursued in order to achieve the landfill diversion goal (Office of the Mayor, 2011). The plan sought to reduce GHG emissions associated with waste processing by transporting it via railcars and barges instead of long-haul trucks which have a worse ecological footprint in comparison, as well as shifting the burden of the waste transfer stations more evenly throughout the city's five boroughs. "...Implementing these strategies will also reduce GHG emissions by 1 million metric tons, decreasing the share of the city's GHG emissions from solid waste management, and reducing the impacts of the system on our communities" (Office of the Mayor, 2011).

Plan Name	*PlaNYC*: A Greener, Greater New York	*OneNYC*: The Plan for a Strong and Just City
Years Active	2007-2013	April 2015-present
Sponsoring Mayor	Bloomberg	De Blasio
Landfill Diversion Goal	75% by 2030	100% ("zero waste") by 2030

Table 2: Comparison of *PlaNYC* and *OneNYC* (Source: Compiled by the authors)

Eight years later in April of 2015, a little over a year after taking office, Mayor Bill de Blasio released *OneNYC*, the updated and renamed version of Bloomberg's *PlaNYC*. *OneNYC* was put under the management of the newly established Mayor's Office of Sustainability (MOS) and the Mayor's Office of Recovery and Resiliency (MORR). The plan took the 75% diversion goal set under Bloomberg even further, calling for a 100% reduction in waste sent to landfills in order to eliminate the environmental impacts associated with exporting our waste to far away landfills **(see Table 2)**. The DSNY is the key agency working with the MOS and MORR to achieve this ambitious zero waste goal. They are focusing on waste reduction, reuse, recycling, and "wastewater treatment plants using food waste for co-generation" to account for 90% of the reduction (Mayor's Office of Sustainability, 2015). No information is provided on how the remaining 10% of landfill diversion will be reached. The plan mentions WtE but only for an organics (food waste) feedstock. There is no specific mention of thermal waste processing in the plan as there had been in Bloomberg's *PlaNYC*. The diagram of the Waste Management System in the plan includes a block for an "Energy Recovery Facility" but none of the Initiatives or Indicators in the plan mention energy recovery. The plan does not describe the types of energy recovery facilities, how they would operate, or where they would be located **(see Figure 4)**.

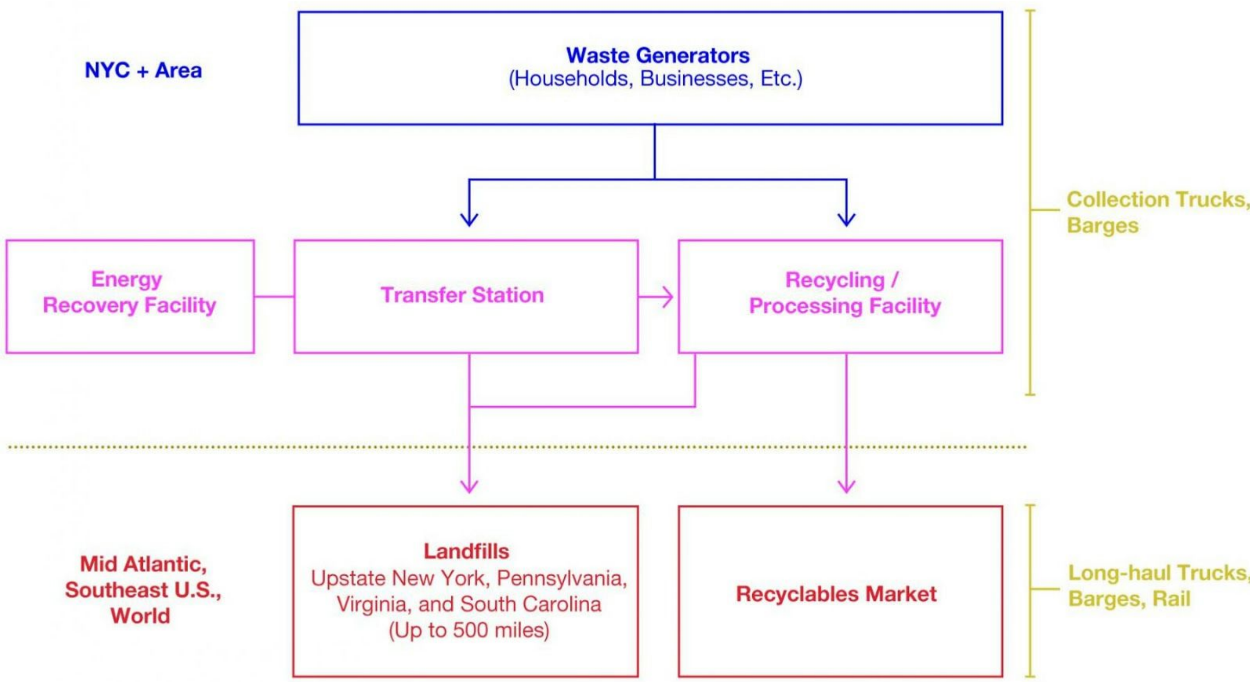

Figure 4: NYC's Waste Management System from *OneNYC*
(Source: Office of the Mayor, 2015)

In addition to *OneNYC*'s zero waste goal, the "80x50" goal – to reduce GHG emissions by 80% by 2050 as compared to 2005 levels – includes an ambitious initiative to improve the environmental impact of the solid waste sector. In comparison, Bloomberg's *PlaNYC* included a "30x30" goal to reduce GHG emissions 30% by 2030 **(see Figure 5)**. The indicator for the initiative to improve the solid waste sector is that an action plan will be developed for how the sector will contribute to achieving this goal (MOS, 2014). The Mayor's Office has pledged that it will hold working groups including multiple stakeholders in order to develop a robust action plan (Mayor's Office of Sustainability, 2015). At this time, no further information has been published on the status of the action plan.

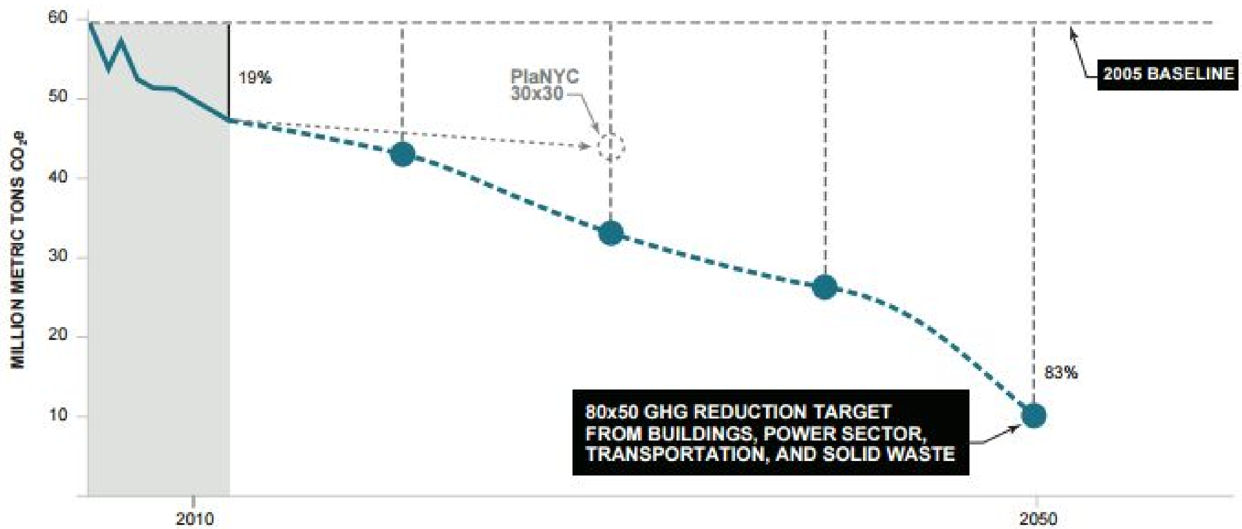

Figure 5: Pathways for Reductions in Citywide Greenhouse Gas Emissions
(Source: Mayor's Office of Long-Term Planning and Sustainability, 2015)

OneNYC is a work in progress with some initiatives and indicators clearly outlined, while some are still in the planning phase. As was the case with Bloomberg's *PlaNYC*, we expect regular updates to the plan to include more specific action plans with increasingly refined targets. As the action plan is being developed for the "80x50" goal, and as the city agencies determine how to handle the 10% of diverted landfill waste that has yet to be planned for, we propose that small- to medium- scale gasification should be explored as a sustainable option for treating a portion of the diverted waste.

4. Waste to Energy

4.1. Waste to Energy Overview

Why should we make a case to research, investigate, and invest in converting waste to energy, or create energy from waste? Why should we look at the new technologies and processes for generating energy from our nation's MSW streams? There are several reasons to investigate WtE as an alternative to landfilling and incineration as the primary means of waste disposal. The rationale for investigating WtE is that it greatly reduces the volume of waste that will need to be disposed in landfills. Additionally, WtE is an alternative means to generating energy that does not rely on combustion of coal, oil and natural gas. WtE can be considered a "transitional technology". WtE can help us deal with our waste while more stringent waste policy is enacted, and while the manufacturing sector moves toward using less packaging and more recyclable materials. As we discussed in examining the Mayor's plans in *OneNYC*, the goals of reducing waste sent to landfill and the reductions of GHGs is of primary importance when looking at the potential for WtE in New York City.

After MSW has been processed through a WtE facility, the typical volume of waste is reduced by 80-90% (Ducharme, 2010). The 10-20% remaining after the thermal treatment of MSW will be an ash consisting of metals, minerals, and uncombusted carbon that can be used as cover for landfills. Alternatively, the ash can be used as an aggregate in concrete or in road bed construction, provided the ash does not contain unacceptably high amounts of heavy metals and toxins such as lead and mercury.

A local WtE facility can reduce environmental pollution emissions from hauling trash long distances to landfills and it can also control emissions emitted from the plants better than landfills without gas capture. WtE can reduce costs for municipalities for waste disposal and could provide a source of income to a facility or municipality for accepting waste from other local municipalities. Additionally, utilization of combined heat and power (CHP) plants for providing heating from steam is another benefit. CHP plants are part of district heating networks, such as the steam network in Midtown Manhattan and steam networks throughout the European Union (EU) (CEWEP, 2014).

For WtE as a source of electricity production, each ton of MSW thermally treated at a WtE plant generates approximately 600-750 kilowatt hours (kWh) of electricity (Ducharme, 2010). Larger scale facilities, such as the Covanta plant in Essex County, New Jersey, accepts 2,800 tons of MSW per day from 22 local municipalities and generates approximately 65 MW of electricity, enough to power 50,000 homes (Covanta, 2015).

Historically, the majority of all waste generated in the U.S is buried in landfills. This includes not only MSW but also industrial wastes and C&D wastes as well. Many of the modern landfills have increased in size due to consolidation of smaller landfills and many are located near high population areas. However, considering that the EPA now considers sorted MSW as a renewable resource when it is used for energy production, it is likely that this trend will change.

Landfilling solid wastes creates many adverse environmental problems that do not disappear once the final layer of sod cover is in place. The major negative environmental impacts from landfills is pollution of groundwater, soil and air. As the material in a landfill decomposes, rainwater percolates down through the various layers of material picking up hazardous substances along the way and resulting in a toxic leachate. In older landfills or poorly constructed modern ones, this leachate enters the groundwater system contaminating it with metals and hazardous organic chemicals. Another environmental problem is the creation of biogas, which is made up of carbon dioxide and methane. This air pollutant is created in stages of anaerobic decomposition of the organic materials within landfills. GHGs from landfills are major contributors to anthropomorphic climate change.

Lack of air and the enduring nature of modern materials means the waste buried in landfills cannot naturally decompose. Plastics and metals, when not removed for recycling, may sit in the landfill perpetually. The remaining wastes create toxic byproducts rather than being usefully reused in a WtE process. Due to the lack of decomposition in a landfill, any land that has been dedicated as a landfill will remain as such for many generations, rendering it unproductive and unavailable for other uses, such as agriculture, recreation, or preserved open space.

As discussed earlier, the U.S. has a waste problem. As our population and per capita wealth has increased over time, so has the volume of waste that we, as a nation, have generated. Approximately 60% of our MSW ends up in landfills which amounts to about 254 million tons as of 2013 (Shin, 2014). The U.S. Census projects that the population may surge to nearly 400 million people by 2050. With that growth there will likely be a significant surge in the overall amount of waste that is generated. As the regulations set by the EPA for operating landfills remain stringent, creating new dump sites to accommodate the projected waste increase seems unlikely and the current landfills will be strained to handle the growing waste stream. The points above lead to an increasing need to find alternative means of disposing of waste, which makes WtE a primary, environmentally beneficial, alternative.

According to the waste management hierarchy from the EPA, WtE is a more preferred form of waste disposal than landfilling **(see Figure 6).** WtE is a step toward a circular economy. Traditional production methods and consumption paths – resource extraction, manufacturing, consumer use, and disposal – follow a linear path and have a corresponding reduction in potential energy use as you get further along in the production process. Waste to energy, however, is a step towards altering the linear path to a more circular closed loop system that retains more of the energy within the system, rather than eliminating it as discarded waste.

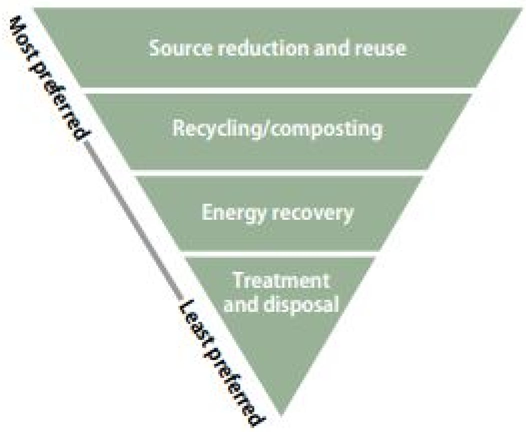

Figure 6: Inverted Pyramid of Waste Management (Source: EPA)

WtE has been more widely adopted as a means of treating MSW in many Scandinavian and European countries than in the U.S. WtE facilities to treat MSW are increasing throughout the EU in response to improved environmental awareness, growing population, and increasing waste generation rates (CEWEP, 2014). We can look to these countries as successful examples of using WtE to reduce or often eliminate landfill disposal of their MSW. Approximately 380 plants are operating in 18 countries according to the Confederation of Waste to Energy Plants. This represents approximately 31 billion kWh of annual electricity production and a reduction of approximately 78 million tons of waste diverted from landfills **(see Figure 7)** (CEWEP, 2014). Comparatively, in the U.S. there are approximately 86 plants, which are mostly combustion, operating in 24 states including New York, Massachusetts, Connecticut, as well as states in the Midwest and in the Pacific Northwest (Energy Recovery Council, 2010). There exist fewer gasification technology facilities for treating MSW worldwide than combustion facilities. In the 1980's, gasification for the treatment of wastes expanded in Europe and Japan, most commonly for thermally converting biomass and coal into synthetic gas fuel products (Ducharme, 2010).

The U.S. should look to the European model on how to utilise WtE as a primary means of reducing the volume of solid waste sent to landfills and achieving zero waste goals. Additionally, using waste to generate electricity reduces our reliance on coal, oil and natural gas for energy production. WtE technologies should be investigated and implemented in order to help reduce GHG emissions associated with waste disposal in landfills.

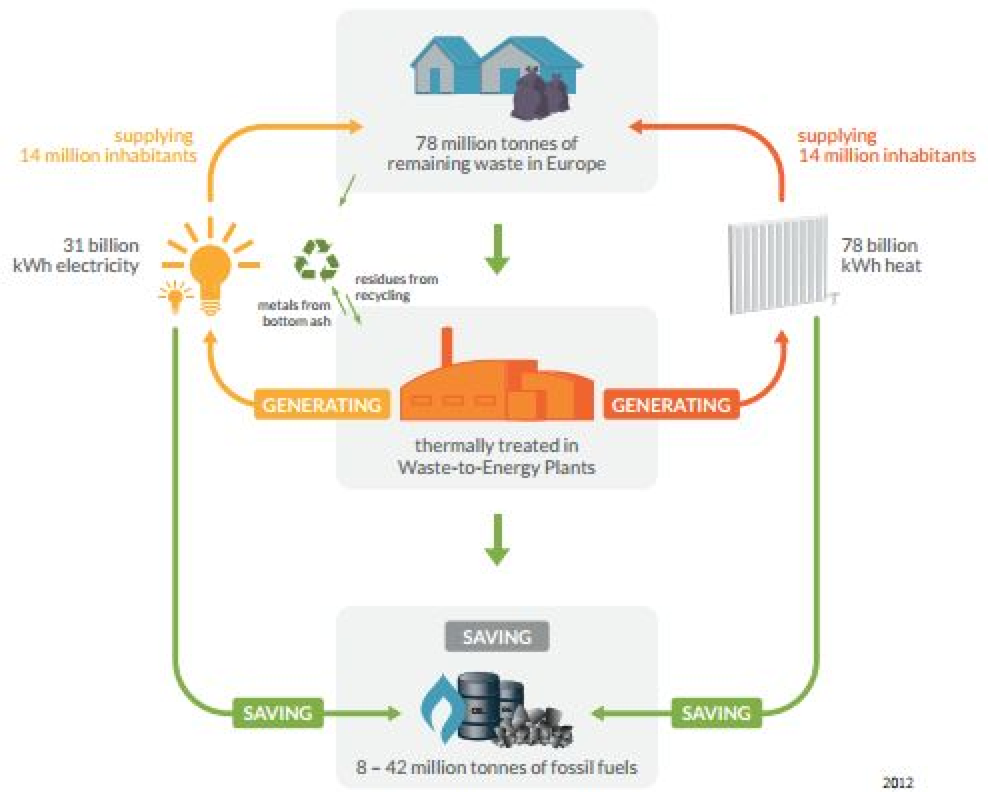

Figure 7: Waste to Energy Cycle (Source: CEWEP, 2014)

4.2. Thermal Conversion Technologies: Combustion and Gasification

Converting MSW into electric or heat energy requires a thermal or chemical treatment process. The dominant technologies for the thermal treatment of large MSW quantities are combustion and gasification. Combustion (incineration) is the more familiar technology as it has been a primary method to reduce and remove MSW from cities since the late 1800's. As a means of generating energy from waste, incineration was used in the U.S. beginning in the 1970's according to the National Renewable Energy Lab (Funk, Milford, & Simpkins, 2013).

Combustion of solid waste, also known as mass burning, continues to be the dominant form of thermal treatment of MSW in the U.S. Combustion of MSW is the burning of waste to generate enough heat to convert water into steam. This steam is used to power turbines which turn generators to create electricity. Many combustion facilities – referred to as cogeneration or CHP facilities – also harvest the process steam to run local district heating.

In most mass burn facilities the waste does not need to be pretreated or sorted; it can be fed into the combustion chamber as-is. At facilities such as the Covanta plant in Union County, NJ, which this group toured, an equipment operator mixes the waste with giant claws to agitate it prior to loading the hopper for the combustion chamber **(see Appendix F.2 for photos)**. The waste is agitated via large grates as it passes through the combustion chambers; these mass burn facilities are sometimes known as grate combustion because of this mechanical feature (Grillo, 2013). The flue gasses generated after combustion then pass through the waterwall furnace where water is heated to produce steam. The steam is used to turn large turbines and then generators to produce electricity. The flue gasses then continue through a separate area in the combustion facility called a baghouse where they pass through various filters that remove particulate matter and a portion of pollutants before being released through the vertical exhaust stack and into the atmosphere.

Gasification consists of the partial oxidation of a solid fuel to produce a synthetic gas which can be used in a number of ways including in gas turbines to generate electricity; in the creation of liquid fuels; or for other chemical materials. It is an alternative to combustion of MSW because of the ability to produce different forms of energy (Castaldi, 2013). Gasification differs from combustion in that (in gasification) the waste is treated under higher temperatures and with less oxygen. Combustion uses anywhere between 50-100% excess air to fully combust the waste feedstock (Grillo, 2013). Due to the amount of excess air required in combustion, the thermochemical reactions that take place produce higher percentages of carbon dioxide and water emissions than in the gasification process (Grillo, 2013). Gasification is up to 18% more thermally efficient than combustion and produces fewer toxins and volatile emissions (Wilson, 2014). Gasification of waste is a much more precise thermal conversion process – and therefore more difficult to design and implement – than combustion.

The U.S. EPA has established stringent requirements for background testing of the emissions levels of power plants as per the 1990 and 2000 updates to the Clean Air Act (CAA) (Funk et al., 2013). Section 129 of the CAA sets "new source performance standards" for small municipal waste combustors (SMWC). To our knowledge, the CAA does not specify standards for small-scale gasification. The limits set in the CAA Section 129 are always evolving as the "best available control technologies" improve and are implemented in new facilities (Funk et al., 2013). The limits are based on the performance of the top 12% of similar units in the facility's category and are set to meet the maximum achievable control technology (MACT) standards (Funk et al., 2013). As technologies continue to evolve and improve, the emissions limits become more stringent. This is reflected in the nationwide drop in toxic emissions from WtE plants by 94% from 1990 to 2005 (Rosengren, 2015).

Emissions which are common for gasification and combustion processes are established and controlled by the *CAA - 40 CFR Part 60 sections 129 and 111(b)* and include the following pollutants: metals (e.g. lead, mercury), acid gases (e.g. hydrogen chloride, nitrogen oxides (NO_x), and sulfur dioxides (SO_x)), and organic dioxins (EPA, 2000). **Table 3** is taken from section 129 Subpart AAAA and lists the emissions limits for SMWC. These regulated pollutants are known to be toxic to humans and cause various adverse health effects. The NO_x, SO_x, and hydrogen chlorine are all major contributors to the acidification of rainwater, or acid rain (Wislon, 2014). In gasification, the processes requires very little oxygen which limits the formation of NO_x and SO_x, making this a better environmentally performing technology than combustion for MSW. Also, less oxygen use reduces the production of dioxins and furans (Castaldi, 2013). Gasification allows for the complete breakdown of compounds to their molecular levels, thus reducing the formation and release of toxins, whereas in combustion, these toxins are difficult to capture and control (Wilson, 2014).

Common among the WtE thermal processes is the generation of residual ash which is reduced to approximately 10% of the original waste volume (Michaels, 2013). This ash is traditionally disposed of in landfills, used in landfill roadbed and as a landfill cover. Other useful applications include as concrete aggregate and in roadway construction. Ash generated from WtE processes has been tested per U.S. EPA standards for levels of toxicity and for non-hazardous materials for many years and the material has been proven to be safe for disposal in a landfill (Michaels, 2013).

For the following pollutants	You must meet the following emission limits[a]	Using the following averaging times	And determine compliance by the following methods
1. Organics			
Dioxins/Furans (total mass basis).	13 nanograms per dry standard cubic meter.	3-run average (minimum run duration is 4 hours).	Stack test.
2. Metals:			
Cadmium	0.020 milligrams per dry standard cubic meter.	3-run average (run duration specified in test method).	Stack test.
Lead	0.20 milligrams per dry standard cubic meter.	3-run average (run duration specified in test method).	Stack test.
Mercury	0.080 milligrams per dry standard cubic meter or 85 percent reduction of potential mercury emissions.	3-run average (run duration specified in test method).	Stack test.
Opacity	10 percent	Thirty 6-minute averages	Stack test.
Particulate Matter	24 milligrams per dry standard cubic meter	3-run average (run duration specified in test method).	Stack test.
3. Acid Gases:			
Hydrogen Chloride	25 parts per million by dry volume or 95 percent reduction of potential hydrogen chloride emissions.	3-run average (minimum run duration is 1 hour).	Stack test
Nitrogen Oxides (Class I units)[b].	150 (180 for 1st year of operation) parts per million by dry volume.	24-hour daily block arithmetic average concentration.	Continuous emission monitoring system.
Nitrogen Oxides (Class II units)[c].	500 parts per million by dry volume	See footnote[d]	See footnote[d]
Sulfur Dioxide	30 parts per million by dry volume or 80 percent reduction of potential sulfur dioxide emissions.	24-hour daily block geometric average concentration or percent reduction.	Continuous monitoring emission system.
4. Other:			
Fugitive Ash	Visible emissions for no more than 5 percent of hourly observation period.	Three 1-hour observation periods	Visible emission test.

[a] All emission limits (except for opacity) are measured at 7 percent oxygen.
[b] Class I units mean small municipal waste combustion units subject to this subpart that are located at municipal waste combustion plants with an aggregate plant combustion capacity more than 250 tons per day of municipal solid waste. See § 60.1465 for definitions.
[c] Class II units mean small municipal waste combustion units subject to this subpart that are located at municipal waste combustion plants with an aggregate plant combustion capacity no more than 250 tons per day of municipal solid waste. See § 60.1465 for definitions.
[d] No monitoring, testing, recordkeeping, or reporting is required to demonstrate compliance with the nitrogen oxides limit for Class II units.

Table 3: Emissions Limits for New Small Municipal Waste Combustion Units
(Source: Table 1: Subpart AAAA of 40 CFR Part 60, EPA Clean Air Act)

Gasification of MSW occurs in two stages which consist of a pyrolysis stage, which occurs in the absence of oxygen, then breaks down the compounds at lower temperatures. A second stage induces oxygen or an air mixture into the chamber which further reacts with the carbon that produces the lower Btu gas (Klein, 2002). The two stages can be thought of as waste to producer gas, and then producer gas to combustion products (Castaldi, 2013). By altering the levels of oxygen in the thermal reactor, the producer gas will have varying levels of nitrogen which will affect the heating value of the gas. The added oxygen in the second stage is an exothermic condition which generates enough heat to aid in the initial pyrolysis stage (Klein, 2002). Below are examples of some of the thermal reactions that occur in the gasification process (Ducharme, 2010). Which of these reactions take place will differ depending on the process and the desired end product gas.

$$C + O_2 \rightarrow CO_2$$
$$C + H_2O_{(g)} \rightarrow CO + H_2$$
$$C + CO_2 \rightarrow 2CO$$
$$C + 2H_2 \rightarrow CH_4$$
$$CO + H_2O \rightarrow CO_2 + H_2$$
$$CO + 3H_2 \rightarrow CH_4 + H_20$$

The gasification reactions listed above are not comprehensive. A producer gas from mixed MSW and C&D is likely to consist of carbon monoxide, hydrogen, carbon dioxide, methane, water, and smaller amounts of hydrogen chloride, hydrogen sulfide, ethane and ethylene**.** Although producer gas is not of high enough quality (e.g. purity, heating value) to act as a direct substitute for methane, or natural gas, it can be added into a natural gas stream at diluted amounts to be burned in certain gas powered turbines.

Gasification thermal reactor designs can be reduced to the two main types – downdraft fixed bed and fluidized bed – for our discussion of MSW treatment. With the fixed bed type reactor the solid waste is added from the top and as it flows downward the oxygen is introduced in stages to maximize the efficiency of converting the waste and to prevent the complete oxidation of the material (Castaldi, 2013). The waste ash is deposited out of the bottom and the producer gas exits near the bottom of the reactor chamber. In a fluidized bed reactor the MSW moves through the reactor as the oxidizer is introduced which allows for a higher rate of reactions between the solid waste and gas to sustain the thermal conversion of the waste, thus making this reactor type function well for treatment of MSW (Castaldi, 2013). The fluidized bed has an upward draft of gas and/or steam mixture through the waste to facilitate mixing and increase the heat transfer and efficiency of the thermal process. Fluidized bed reactors have an advantage over other types because of the better mixing and heat transfer rates as well as the uniform and efficient reactions (Klein, 2002).

The production of tars is a problem with gasification and is an impediment to large scale adoption of technology which uses producer gas directly in an internal combustion system for generating electricity (Klein, 2002). Tars consist of both organic and inorganic materials and vary according to type of feedstock. These longer chain carbon compounds do not break down in lower temperatures and can accumulate in the gasifier reactor components, limiting process efficiency (Castaldi, 2013). As temperatures increase the tars will decompose into lesser quantities (Klein, 2002). The tars either have to be processed and broken down further for use in the producer gas or added to the waste stream. Breaking down the tars can be performed by thermal, chemical, or physical means (Klein, 2002).

5. Brooklyn Navy Yard

5.1. Brooklyn Navy Yard Overview

The Brooklyn Navy Yard is a dynamic mixed use business and industrial park located across the East River from Manhattan **(see Figure 8)**. The Yard has over 330 businesses, 7,000 employees, 40 buildings, four active piers and three functioning dry docks spread out over 300 acres (BNYDC, 2015). **(See Appendix A, "Brooklyn Navy Yard Visitor Map" for location of buildings by number.)** The Yard was originally established in 1801 by President John Adams as a naval shipyard, which was its primary function until it closed in 1966 with over 9,000 employees (BNYDC, 2015). The Yard reopened in 1969 but faced difficulties in maintaining successful business and employment numbers despite receiving significant loans from Congress (BNYDC, 2015). The City of New York owns the Yard but has granted its management to the not-for-profit Brooklyn Navy Yard Development Corporation (BNYDC) since 1981. The BNYDC has been successfully developing the site ever since. The Yard enjoys significant benefit from being owned by the city, most notably the lack of imposed or collected property taxes (Pratt Center, 2013).

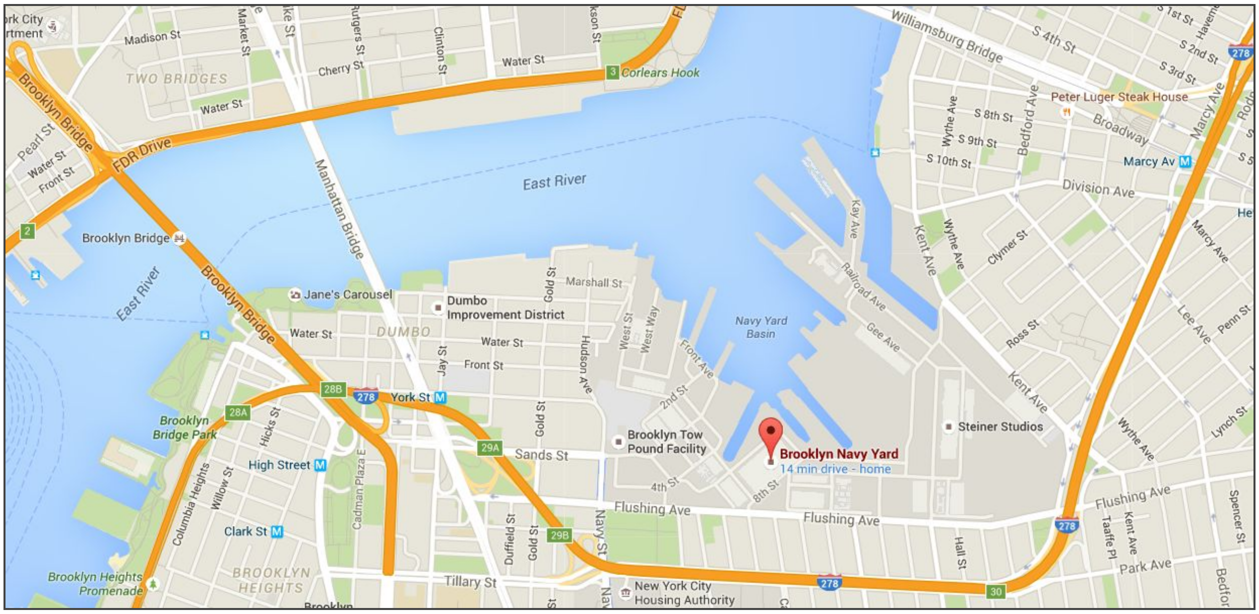

Figure 8: Map of Brooklyn Navy Yard Site in New York City (Source: Google Maps)

The Yard currently employs approximately one tenth of its peak employment reached during World War II when 70,000 people – nearly one percent of the country's workforce at that time according to BNYDC CEO David Ehrenberg – were employed working in the shipyard (Clark, 2015). The Yard is experiencing a resurgence; employment numbers are on the rise and are projected to double by 2020 **(see Figure 9)**. At 7,000 employees the Yard currently is still 2,000 shy of the number of people employed there when it was shuttered in 1966, but it has nearly doubled its 3,600 employees from 2001 (Croghan, 2015). As of a 2013 study of the Yard, Steiner Studios had a significant footprint, holding 10% of all leased space but making up only 2% of all tenants (Pratt Center, 2013). However, their presence at the Yard is expanding with a projected 2,200 additional jobs along with heavy funding and investment for the newly branded Steiner Media Campus which will include academic and media facilities (BNYDC, 2015).

Figure 9: BNY Employment Figures (Source: the authors)

The majority of the projected growth will stem from the two million square feet of rentable space being added to the Yard, largely accounted for by three key developments: Building 77, Admiral's Row, and The Green Manufacturing Center at building 128 (Croghan, 2015). Building 77 alone is nearly one million square feet and will feature a publicly accessible area, a move that will further expose the area to future tenants and potential customers. The cornerstone of the Admiral's Row development is a new Wegman's grocery store slated to open in late 2017 and employ 600 people, 200 of which will be full-time, with an emphasis on hiring people from the neighboring housing projects (Chaban, 2015). Building 128 – the Green Manufacturing Center – is the Yard's showcase on sustainability and innovation **(see Appendix F.3 for photos)**. The $50 million, 220,000 square foot building will host anchor tenants Crye Precision and Macro Sea's New Lab, a collaborative, technological incubator space for designers and inventors (Schram, 2014). In line with the Yard's emphasis on sustainability, the shell of the building was preserved according to adaptive reuse principles and the building will be LEED certified.

Part of BNYDC's sustainability goal is to "Position the Yard to be a national model for sustainable industrial parks in terms of green technology and sustainability" (BNYDC, 2015). It appears they are doing well toward achieving their goal. A two-year study conducted at Pratt Institute found that the Yard's focus on sustainable operations and business practices is a key factor in its success as well as a critical component of its replicability at other former former industrial sites (Pratt Center for Community Development, 2013). The Yard has supported many other sustainable initiatives, including serving as a testing area for the docking stations of the recently implemented CitiBike bike share program, as well as for wind-powered street lights from tenant Duggal.

The type of tenants at the Yard and their waste streams – in terms of quantity and composition – varies greatly and has yet to be profiled in a publically available report. The types of tenants include a fish wholesaler, ship builder, furniture maker, designers, modular construction manufacturer, and set builders, among many others. Additionally, the Yard already has a relatively robust organics stream produced from Kings County Distillery, Brooklyn Grange rooftop farm and Rooftop Reds vineyard. When Wegman's grocery store opens in late 2017 the organics stream will increase significantly. As the city strives for zero waste to landfills by 2030, the Yard will need to devise a plan to account for their waste processing and disposal. Recyclables should all be removed from the waste stream so they can be properly processed instead of combined with general waste. Organics should ideally be processed together, separate from the regular waste stream, with energy capture or creation of nutrient-rich compost that can be sold or used on-site as a soil additive. The remaining fraction of the waste stream – those items that are not organics (e.g. food waste) or are not currently recyclable – needs a sustainable disposal method. Traditionally, most waste has been hauled to landfills in other states where it sits and negatively affects the environment in a community distant from the waste generator. As outlined later in this report, we propose thermal gasification as the solution for processing that remainder of the waste stream that has no other useful life other than to be processed for energy recovery.

5.2. Historical Incineration Plan for the Brooklyn Navy Yard

By the 1980s, with the number of intra-city waste destinations limited by incinerator and landfill closures, the city of New York formulated a plan to build eight to ten WtE incinerator plants. The first plant, which would have incinerated 3,000 tons of MSW per day (approximately 15% of New York City's total waste stream) to create steam to sell to ConEd, was to be built at the BNY and would have cost an estimated $300 million. The plant would have had four furnaces and, with a 500 foot high stack, would have been the largest incineration plant in New York State (Gandy, 1995). The city awarded the contract to build and operate the BNY plant to Signal Environmental Systems in 1985 (Associated Press*,* 1985).

The plan to build a WtE incineration facility in the BNY was on hold for more than seven years due to opposition from stakeholders at every level. At the top, the New York State Commissioner for Environmental Conservation Thomas C. Jorling had withheld approval, citing concerns over New York City's ability to meet regulatory standards for ash disposal. The Brooklyn Borough President in the early 1990s, Howard Golden, had called the proposed plant, with its 500-foot high smokestack towering over the neighboring areas, a "monstrosity". The members of the Williamsburg community, with the leadership and assistance of religious leaders and lawyers, fought the project because of the fear of potential health risks (Barbanel, 1985). By 1993, Commissioner Jorling approved the BNY plan stating he was "satisfied that New York City had a firm commitment to meet the regulatory standards for the disposal of ash" (Hevesi, 1993). Ultimately, however, the plant was never built because of strong community opposition.

6. Proposal: Gasification at the Brooklyn Navy Yard

6.1. Proposal Overview

This section explains in detail the waste to energy solution that we designed for the Brooklyn Navy Yard. The many factors to consider for building a new WtE system include, but are not limited to location availability, cost, the quantity and composition of waste, and the needs and wants of the energy customer. In addition, in an increasingly polluted environment it is important to create a system that will result in net-negative GHG emissions.

The WtE solution also must be planned and sited in a manner that takes into consideration the concerns of the local community. The neighborhoods surrounding the BNY are very densely populated. A large scale housing development, the New York City Housing Authority Walt Whitman Houses, is one block away and houses about 4,276 people in 1,636 apartments within 15 buildings ("Walt Whitman Houses", 2015). New housing developments have been planned, or have been recently built adjacent to the BNY, including the income restricted "Navy Green" condominiums on Vanderbilt Avenue ("Navy Green Condominium Application", 2015). As is typical with mixed-industrial areas, truck traffic and noise are community concerns around the BNY. The WtE proposal for the BNY also must consider noise pollution concerns and must not exacerbate traffic issues.

6.2. Why Gasification

This project aims to assist the existing Brooklyn Navy Yard Cogeneration facility in providing the BNY with district steam heating and electricity. The BNY Cogen facility is located in Building 41 of the BNY. It produces 286 MW of power through a "Siemens Combined Cycle" cogeneration (producing both electricity and steam) system (Brooklyn Navy Yard Cogeneration Partners, n.d.). The BNY Cogen system includes two Siemens SGT6-2000E gas turbines ("Siemens Press Releases", 2015). **Figure 10** shows the blades of the SGT6-2000E turbine.

Figure 10: Siemens SGT6-2000E Gas Turbine Blades (Source: Siemens Energy)

The Siemens SGT6-2000E gas turbines are capable of using a wide variety of fuels, including producer gas, heavy fuel oils, low calorific fuels, and dual fuels ("Siemens Gas Turbine - SGT-200E Series", 2011). If the SGT6-2000E gas turbines at the BNY Cogen facility are not yet optimized for use with flex fuels or producer gas derived from waste, Siemens offers a "Fuel Conversion" upgrade ("Siemens Fuel Conversions", n.d.). The fuel used in the BNY Cogen facility is natural gas imported from various locations in the U.S. and Canada. BNY Cogen has found itself locked into above-market natural gas supply contracts. One goal of the BNY WtE project is to decrease the BNY Cogen's reliance on natural gas purchased from outside of New York State and transported great distances. A substitute for natural gas could also be used by BNY Cogen in peak demand periods to reduce their demand pricing charges.

On April 18, 2015, the VP of Maintenance for the BNYDC led the project team on a bicycle tour of the BNY **(see Appendix F.3 for photos)**. The project team was told that tenants are responsible for their own waste disposal and hauling. Tenant waste quantities and compositions are not tracked by BNYDC. The project team counted the dumpsters adjacent to all BNY buildings. The VP of Maintenance provided the team with information about the frequency of collection by waste handling companies for the various buildings. Through the dumpster count and collection frequency information, the project team determined that BNY produces approximately 30 tpd of mixed refuse (a combination of MSW and C&D waste).

The project team met with the Projects General Manager of Power Plant Management Services, LLC on May 13, 2015 **(see Appendix F.4 for photos)**. He presented the project team with pressure and quality specifications of the BNY Cogen facility's natural gas flow. BNY Cogen would welcome any amount of producer gas of appropriate composition, pressurized to match the their natural gas flow. He expressed interest in the idea that producer gas produced by an on-site WtE facility could assist with electricity and steam production, especially during peak demand periods.

Less than 2% of the 286 MW produced by BNY Cogen is used to provide electricity and district steam heating to the BNY; ConEd purchases more than 98% of the energy. ConEd uses electricity from BNY Cogen to power parts of Manhattan, Brooklyn, and Queens and it uses steam from BNY Cogen for district heating in a portion of lower Manhattan. The project team communicated with a ConEd Senior Engineer throughout the project. Through email, the engineer informed the project team that ConEd is actively exploring alternative energy projects and the company would be welcoming of a WtE component in their energy production system. During an in-person meeting with the project team on October 15, 2015, the ConEd Senior Engineer explained environmental permitting for energy facilities; he also provided information about ConEd's steam pressure requirements and answered general technical questions.

6.3. Technological Solution

The WtE system we designed consists of several components: the shredder, the gasifier, the ash containment area, the producer gas storage tank, producer gas transmission pipes to BNY Cogen, the waste collection shed, and monitoring equipment. **Figure 11** illustrates the proposed process. The following sections describe the system components in detail.

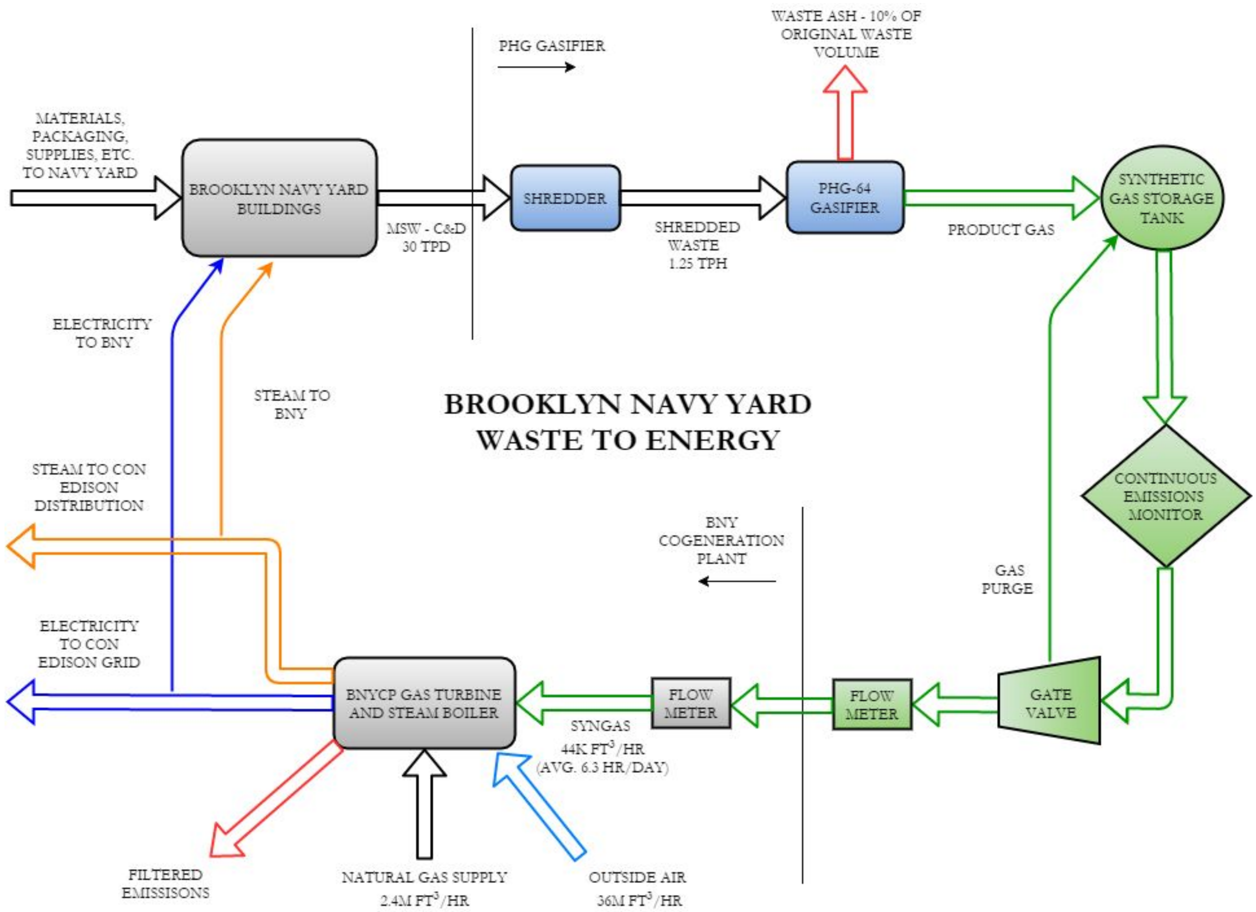

Figure 11: Brooklyn Navy Yard Waste to Energy Process Diagram
(Source: The authors)

Shed for Collected Waste and Shredder:

An agreement among the BNY tenants will be negotiated such that industrial tenants with forklifts will be paid a small fee (to be determined) to bring the waste from throughout the Yard to the waste gasification facility. After the detailed project design is completed, it may be clear that the cost-effective solution is for a separate dedicated company to be formed to collect the waste. The waste will be brought to a waste collection shed with sufficient capacity to hold two days of garbage, or approximately 60 tons. With the assumption that 1 yd^3 of mixed waste at the BNY weighs 500 lbs, the volume of each ton of waste is 4 yd^3. Thus, the volume needed to hold 60 tons of waste is 240 yd^3. A shed of dimensions 30 ft x 60 ft and 20 ft tall has a floor area of 1800 ft^2, or 200 yd^2. This size building has the capacity to hold the piled collected waste and the shredder. We estimate the shredder footprint will fit within a 10 ft x 10 ft area.

Shredder System:

The Quad 85 (Q85) low speed high torque (LSHT) shredder system was selected from SSI Shredding Systems, Inc. to process the waste from the Yard before it is fed into the gasifier **(see Figure 12)**. A LSHT system was chosen because it has a lower noise and dust output than other types of shredder systems, two critical requirements for a densely populated urban site. The Q85 LSHT system has many other advantages over a high speed system, including lower installation requirements, durability, and a wider range of acceptable feedstock. The shredder will operate for 8 hours per day to allow downtime for maintenance and safety concerns. With our estimated 30 tpd of waste from the yard, the system will shred 3.75 tons per hour to a particle size of two inches. We assume that all recyclables will be removed before the waste is shredded. Any metals that remain in the waste stream will be separated out in the gasification process.

Figure 12: Quad 85 Shredder
(Source: SSI World) (above)
Figure 13: PHG-64 Gasifier Unit
(Source: PHG Energy) (right)

Gasifier System:

The PHG-64 gasifier unit from PHG Energy was selected because it is scalable, modular, and is successfully used in other gasification projects **(see Figure 13)**. We need a system that can process at least as much waste as we've estimated the yard produces on a daily basis (30 tpd). However, we also want a system that can accommodate an increasing waste stream as the yard continues to grow and develop. BNY has ambitious growth plans and we want our system to be able to scale up along with the Yard so it can continue to divert waste from landfills. **Figures 14 and 15** show details of the PHG-64 gasification process.

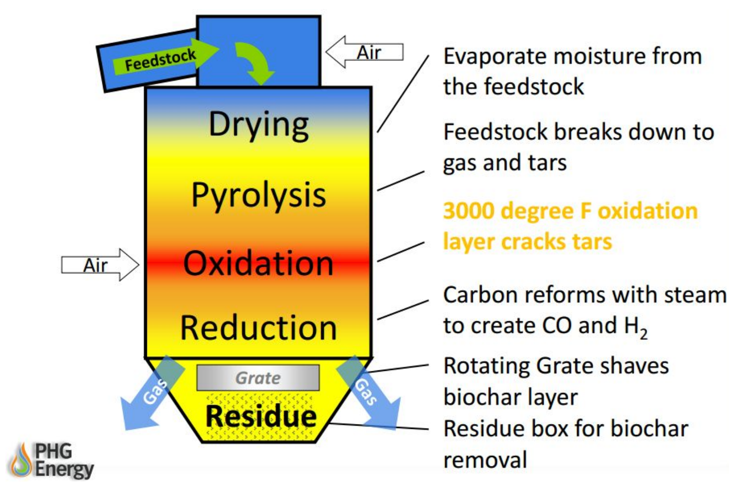

Figure 14: Converting Solids to Fuel Gas (Source: PHG Energy)

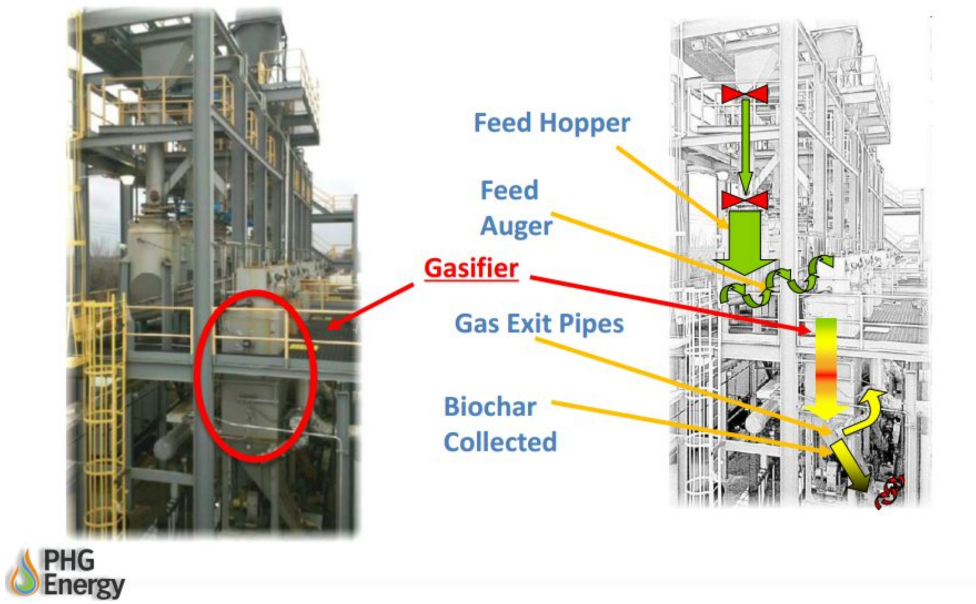

Figure 15: The Flow of Material to Gas (Source: PHG Energy)

Producer Gas Storage Tank:

The producer gas will flow from the PHG-64 gasifier directly into a vertical pressurized tank. The storage capacity will be sufficient to contain seven days of producer gas. When the BNY Cogen turbine is undergoing maintenance, the gas flow will be held in reserve until needed. Extra capacity also allows BNY the flexibility to use the gas in periods of particularly high demand. The storage tank manufacturer is to be determined.

Producer Gas Piping:

The gas will be piped from the pressurized gas storage tank to BNY Cogen. The pipe size will be based on the flow and pressure of the gas. An engineer specializing in fluid mechanics will be consulted to design the system architecture. The gas lines will be welded on site.

Monitoring and Flow Control Equipment:

The producer gas will flow from the pressurized gas storage tank to BNY Cogen. For emissions control purposes, the producer gas composition will be monitored. An on-line gas analyzer such as the "MultiGas 2030" by MKS Instruments, Inc. can monitor all of the compounds in the producer gas, ensuring the gas is consistent enough for use by BNY Cogen **(see Figure 16)**. The producer gas flow will be metered by an instrument such as the American Meter Gas Turbine Meter, shown in **Figure 17**. The producer gas flow can be shut off if necessary by a valve such as the IMAC Cami-valve shown in **Figure 18**.


Figure 16: MKS Instruments, Inc. MultiGas 2030 (Source: MKS Instruments) (left)
Figure 17: American Meter Company Gas Turbine Meter (Source: IMAC Systems) (middle)
Figure 18: IMAC Cami-valve (Source: IMAC Systems, Inc.) (right)

Since the gas is already at a high pressure from being in the pressurized tank, we have to connect the producer gas line to the natural gas supply line after the natural gas has been compressed. A compressor or other pressure regulator is needed to bring the gas to the pressure matching the compressed natural gas pressure at the turbine inlet.

6.4. Calculations

Calculations for this project are extensive and pertain to the heating values of gases, the energy in the BNY Cogen natural gas stream, the energy and flow of the producer gas created in the gasifier chosen, the storage of the producer gas before it is used by BNY Cogen, the air-to-fuel ratio in the BNY Cogen turbine, the total gaseous flow in the turbine, the hydrocarbons in the producer gas, and the emissions produced by using the producer gas to generate electricity. The following equivalences are helpful for the project calculations:

- 1 ft^3 of natural gas is approximately equal to 1,000 Btu
- A Dth is a "decatherm"; 1 Dth/hr = 1 MMBtu/hr

In an email from May 14, 2015, the Projects General Manager of Power Plant Management Services, LLC provided the following partial list of requirements for the producer gas produced by the gasifier:

- gas temperature between 27°F and 248°F
- heat value between 15,050 and 24,500 Btu/lb
- acetylene – max 1% by volume
- hydrocarbons – max 10% by volume
- pressure – 260 psi

<u>Heating Values</u>

The heating values used in this project specifically refer to the lower heating value (LHV), also known as the net heating value, and have units of either Btu/lb or Btu/ft^3 **(see Table 4)**. MSW and C&D wastes when gasified are composed of various chemical compounds and could include CO, H_2, CO_2, CH_4, H_20, HCl, H_2S, C_2H_6, C_2H_4, and N_2. **Tables 5 and 6** show percentages of the various chemical compounds assumed to be present in the gas produced from gasification of MSW and C&D at the BNY.

Lower Heating Values (LHV) by Compound										
	CO	H2	CO2	CH4	H20	HCl	H2S	C2H6	C2H4	N2
Btu/ft3	323	275	0	910	0	0	596	1,630	1,530	0
Btu/lb	4323	51605	0	21537	0	0	6545	20,394	20,298	0

Table 4: Lower Heating Values by Compound (Source: "Gross and Net Heating Values", n.d.)

Characterization of Gasification of MSW											
	CO	H2	CO2	CH4	H20	HCl	H2S	C2H6	C2H4	N2	TOTAL
% of Compound in MSW	41	33.7	13.8	4.1	6.3	0.13	0.13	Trace	Trace	Trace	**99.16**
LHV of Compound (Btu/ft3)	132.43	92.68	0.00	37.31	0.00	0.00	0.77	0.00	0.00	0.00	**263.19**
LHV of Compound (Btu/lb)	1772.43	17390.89	0.00	883.02	0.00	0.00	8.51	0.00	0.00	0.00	**20054.84**

Table 5: Characterization of Gasification of MSW (Sources: Klinghoffer and Castaldi, 2013; "Gross and Net Heating Values", n.d.)

Characterization of Gasification of C&D											
	CO	H2	CO2	CH4	H20	HCl	H2S	C2H6	C2H4	N2	TOTAL
% of Compound in C&D	17.1	41.1	17.1	11.1	10.0	Trace	Trace	0.9	2.6	Trace	**99.90**
LHV of Compound (Btu/ft3)	55.233	113.025	0	101.01	0	0	0	14.67	39.78	0	**323.72**
LHV of Compound (Btu/lb)	739.23	21209.66	0.00	2390.61	0.00	0.00	0.00	183.55	527.75	0.00	**25050.79**

Table 6: Characterization of Gasification of C&D (Sources: The authors through discussion with project advisor Prof. Castaldi; "Gross and Net Heating Values", n.d.)

Assuming a 50:50 mix of MSW and C&D requires averaging the heating values for MSW and C&D, resulting in a producer gas heating value of 22,553 Btu/lb or 293.45 Btu/ft^3. The producer gas heating value of 22,553 Btu/lb is within the range requested by BNY Cogen (15,050-24,500 Btu/lb).

Energy and Flow Rate of BNY Cogen Natural Gas Stream

The Projects General Manager of BNY Cogen provided a spreadsheet of hourly natural gas flows into the cogen plant. Averaging the hourly data for the years 2014 and 2015 to-date, and removing the zero values, yielded an hourly natural gas rate of 2,395.65 Dth/hr which is equal to 2,395.65 MMBtu/hr. For natural gas, 2,395.65 MMBtu is approximately equivalent to 2,395,650 ft^3/hr. Therefore, the flow rate of natural gas into BNY Cogen is 2,395,650 ft^3/hr.

Energy and Producer Gas Flow Produced by the Gasifier

The energy produced by the PHG-64 gasifier using 30 tpd of mixed (50:50) MSW (LHV of 10,000 Btu/lb) and C&D (LHV of 8,200 Btu/lb) was provided by the representative of Sherwood-Logan & Associates, Inc. (distributor of the PHG-64 system) as 16.2 MMBtu/hr (gross), 13 MMBtu/hr (net). The net value of 13 MMBtu/hr is used for calculations. Comparing the amount of energy produced by the gasifier with the energy in the natural gas stream flowing into BNY Cogen:

$$13 \text{ MMBtu/hr} \div 2{,}395.65 \text{ MMBtu/hr} = 0.0054 = 0.54\%$$

of the energy of the natural gas supply to BNY Cogen.

2,395,648 ft^3/hr is the existing average flow rate of the natural gas into the Cogen plant. The amount of producer gas our project creates will replace a small fraction of the Cogen plant natural gas stream. The heating value of the BNY Cogen natural gas stream has a higher heating value than the producer gas so more producer gas will need to be supplied to provide the same amount of energy as exists in the natural gas replaced by the producer gas. The natural gas heating value is 1,000 Btu/ft^3. The producer gas heating value is not precisely known but by assuming the composition of the producer gas produced by the gasifier, we calculated a heating value of 293.45 Btu/ft^3; therefore, the flow of the producer gas will be need to be 3.41 times as high

$$1{,}000 \text{ Btu/ft}^3 \div 293.45 \text{ Btu/ft}^3 = 3.41.$$

The volumetric flow rate of our gas will be

$$0.54\% \times 2{,}395{,}648\ ft^3/hr \times 3.41 = 44{,}113\ ft^3/hr.$$

The information provided by Sherwood-Logan & Associates assumes the gasifier will be operating 7884 hours/year, which amounts to 21.6 hours/day; however, since the producer gas is being supplied to BNY Cogen at a faster rate than it is being produced, the gas will be supplied for an average of 6.3 hours/day

$$21.6\ hours/day \div 3.41 = 6.3\ hours/day.$$

BNY Cogen can draw the producer gas from its storage tank when its natural gas supply is most expensive, such as peak demand times. The logistics of supplying the producer gas at a faster rate than the natural gas must be worked out in the fluid mechanics design.

Since our gas will replace a fraction of the natural gas into the BNY Cogen plant, during the 6.3 hours/day (on average) the producer gas is used, the BNY Cogen gas stream will be 2,382,711 ft^3/hr:

$$0.54\% \times 2{,}395{,}648\ ft^3/hr = 12{,}937\ ft^3/hr$$

$$2{,}395{,}648\ ft^3/hr - 12{,}937\ ft^3/hr = 2{,}382{,}711\ ft^3/hr.$$

With the addition of the extra producer gas, the total flow of producer gas plus natural gas will be

$$2{,}382{,}711\ ft^3/hr + (44{,}113\ ft^3/hr - 12{,}937\ ft^3/hr) = 2{,}413{,}887\ ft^3/hr.$$

Producer Gas Storage

For large quantities of gas, a compressed tank is necessary otherwise the gas storage tank will be prohibitively large. The PHG-64 gasifier is expected to produce 13 MMBtu/hr of energy net. The flow rate leaving the gas storage tank and entering BNY Cogen is 44,113 ft^3/hr (calculated above). BNY Cogen can receive producer gas for up to 6.3 hours/day on average. The producer gas storage tank will provide up to seven days (of up to 6.3 hours/day) of 44,113 ft^3/hr flow.

$$7\ days \times 6.3\ hours/day \times 44{,}113 ft^3/hr = 1{,}945{,}383\ ft^3.$$

Although this is a very large quantity of gas, storing it under pressure will reduce the size of the tank required. Discussion with our advisor Prof. Castaldi led us to a pressurized tank size of 4 meters (13.12 ft) diameter and 10 meters (32.81 ft) tall. The height of the tank will be similar to the height of the gasifier.

Note: the actual flow rate of producer gas produced by the gasifier may be different due to varying assumptions about the heating value of the waste. The PHG gasifier representative assumed a much lower average heating value than we have calculated. If, after a more detailed per-tenant analysis of the BNY waste stream, the average heating value of the available waste is different than expected, the producer gas storage tank size may need to be recalculated to allow more capacity.

Air-to-Fuel Ratio in the BNY Cogen Turbine

In order to burn the gas to drive the turbine, a large amount of air is added. The "stoichiometric air-to-fuel ratio" of natural gas by volume is 9.7 to 1, which means that 9.7 parts air is added to completely combust every 1 part of natural gas. Because natural gas is expensive, however, air-to-fuel ratios are larger than the stoichiometric air-to-fuel ratio in order to eliminate the possibility of wasting the natural gas. The Projects General Manager of Power Plant Management Services, LLC provided us with the actual air-to-fuel ratio in the Siemens SGT6-2000E gas turbine used in the cogeneration plant: 44 to 1. There are 44 parts air to every one part gas.

Total Flow in the Turbine

We sum the quantity of the air + natural gas + producer gas to determine the total flow during the 6.3 hours/day (on average) the producer gas is supplied to BNY Cogen. If the total natural gas plus producer gas mixture flowing through the process is 2,413,887 ft^3/hr, then the air total is 44 times larger:

$$2{,}413{,}887 \text{ ft}^3/\text{hr} \times 44 = 106{,}211{,}028 \text{ ft}^3/\text{hr}.$$

To achieve the total air + fuel gases, we sum

$$2{,}413{,}887 \text{ ft}^3/\text{hr} + 106{,}211{,}028 \text{ ft}^3/\text{hr} = 108{,}624{,}915 \text{ ft}^3/\text{hr}.$$

We will use this quantity to determine the emissions created by combusting the producer gas we contribute.

Power Created by the Producer Gas

The transfer of energy in the gas to power is limited by the efficiency of the turbine. (For our simplicity we neglect other losses in our calculations.) The Siemens gas turbine has a gross efficiency of 34.3%. The overall BNY Cogen plant efficiency is higher because of heat recovery and steam production downstream of the gas turbines. Assuming all the energy in the product gas is preserved from the gasifier to the turbine (neglecting any potential losses in piping and storage), and using the energy produced by the gasifier value (13 MMBtu/hr) provided by the PHG system representative,

$$13 \text{ MMBtu/hr} \times 0.343 = 4.5 \text{ MMBtu/hr}.$$

We will use this value later to determine how much of the Yard's energy consumption could be provided by the product gas in our gasification system.

Hydrocarbons in the Producer Gas

The Projects General Manager of Power Plant Management Services, LLC specified that the producer gas must have less than 10% hydrocarbons by volume. The percentage of hydrocarbons (not including methane) in the synthesis gas will be 1.8% (assuming 50:50 mix of MSW and C&D wastes, using gas compositions found in our heating value tables), and is well below the 10% requested by BNY Cogen. (MSW gas composition: 0% C_2H_6, 0% C_2H_4; C&D gas composition: 0.9% C_2H_6, 2.6% C_2H_4. Summing the total hydrocarbon percentages for both MSW and C&D yields 3.5%, dividing by 2 gives 1.8%.)

Emissions

Two compounds of particular environmental concern in the producer gas are HCl and H_2S. The Projects General Manager of BNY Cogen provided the project team with a document called NYS DEC Air Title V Facility Permit for the BNY Cogen plant **(see Appendix B)**, but it does not limit chlorine or sulfur emissions because the BNY Cogen fuel is natural gas (mostly CH_4). We looked to the U.S. EPA Clean Air Act for guidance about chlorine and sulfur emissions. Although we could not locate U.S. EPA emissions limits for small gasification facilities, presumably because there are few similar projects in the U.S., we have located U.S. EPA limits for emissions at "small municipal waste combustion units" **(see Table 3)**, defined as incinerators processing between 35-250 tons of garbage per day (EPA, 2000).

Chlorine and sulfur are found in the HCl and H_2S fractions of the producer gas created from gasification of MSW. The amount of chlorine and sulfur exiting the stack of the BNY Cogen plant can be estimated. Although some amount of chlorine and sulfur might remain in the ash after combustion of the gases and may also be partially removed in the Siemens SGT6-2000E turbine, to be conservative we assume all chlorine and sulfur in the process exits the stack. Knowing the fractions of HCl and H_2S in the waste **(see Tables 5 and 6)**, the molar masses of HCl and H_2S, and the total flow of the gaseous mix in the turbine will allow for calculation of the chlorine and sulfur emissions from the stack.

For chlorine, the percentage of HCl in the producer gas is assumed to be 0.13% **(see Tables 5 and 6)**. The molar mass of HCl is 36.4609 g/mol; of that, 1.00794 g is hydrogen (2.7644%) and 35.453 g is chlorine (97.2356%). The percentage of chlorine in the waste stream is therefore

$$0.13\% \times 97.2356\% = 0.1264\%.$$

The total flow of producer gas is 44,143 ft^3/hr, of which half (22,056.5 ft^3/hr) is from the MSW. Next, the total chlorine in the MSW-derived producer gas flow can be determined:

$$22{,}056.5\ ft^3/hr \times 0.1264\% = 27.8794\ ft^3/hr$$

of chlorine. To find the total fraction of chlorine in the gaseous flow (producer gas + natural gas + air), divide the chlorine flow by the total gaseous flow:

$$27.88\ ft^3/hr \div 108{,}624{,}915\ ft^3/hr = 0.000000256 = 0.0000256\%.$$

Similarly for sulfur, the percentage of H_2S in the producer gas is also 0.13% **(see Tables 5 and 6)**. The molar mass of H_2S is 34.0908 g/mol, of which 5.9150% is hydrogen and 94.0850% is sulfur. The percentage of sulfur in the MSW waste stream is

$$0.13\% \times 94.0850\% = 0.1223\%.$$

To find the amount of sulfur in the MSW-derived producer gas flow, multiply

$$22{,}056.5\ ft^3/hr \times 0.1223\% = 26.9751\ ft^3/hr$$

of sulfur. To find the total fraction of sulfur in the gaseous flow (producer gas + natural gas + air), divide the sulfur flow by the total gaseous flow:

$$26.9751\ ft^3/hr \div 108{,}624{,}915\ ft^3/hr = 0.000000248 = 0.0000248\%.$$

Referencing **Table 3**, the CAA limits HCl to 25 parts per million (ppm). By our calculations, the chlorine in the emissions will be 0.0000256%, or 0.256 ppm. The CAA also limits SO_2 to 30 ppm. Our producer gas contains H_2S which oxidizes to SO_2 in combustion. By our calculations, the sulfur in the emissions will be 0.0000248%, or 0.248 ppm. The calculated emissions for chlorine and sulfur in the proposed facility are extremely low compared to the CAA limits.

6.5. Benefits and Costs

This section will quantify project costs and benefits. Some costs are known, such as quoted costs from manufacturers of the gasification system components and some are assumed, such as waste carting costs and producer gas piping. Where the costs are unknown we will aim to estimate conservatively. We anticipate that utilization of the gasification WtE system in the BNY will result in financial savings to the tenants, as well as more difficult to quantify environmental benefits. Costs and savings are outlined in the following sections.

Summary of Costs for Proposed System Components

Table 7 compiles the proposed system component capital costs and operations and maintenance (O&M) costs which include labor. Detailed explanations follow.

Component	**Capital (one time)**	**O&M incl. Labor (annual)**
1. Shed for Collected Waste and Shredder	$25,000	N/A
2. Q85 Shredder System	$383,900	$72,270
3. PHG-64 Gasifier	$5,635,000	$236,284
4. Producer Gas Storage Tank	$150,000	N/A
5. Ash Containment	N/A	$10,950
Subtotal	$6,193,900	$319,504
6. Additional Equipment (producer gas piping, gas composition monitoring, valves, flow meters, etc.), estimated as 10% of designed subtotal	$619,390	N/A
7. Engineering design, legal services and incidentals, estimated as 20% of designed subtotal	$1,238,780	N/A
Total	**$8,052,070**	**$319,504**

Table 7: Estimated Costs of Proposed Waste to Energy Gasification Project at BNY
(Source: The authors)

Detail of Costs for Proposed System Components

1. Shed for Collected Waste and Shredder: **$25,000** (estimated)

2. Shredder System

   Capital cost: $383,900

   Explanation: Selecting the following options from SSI Model Q85 Quad Shredder quote from Rich Ellis of SSI World: Q85 Shredder $269,000; "Patented hydraulic ram assist hopper", $32,000; "Hood for hopper", $7,100; "1.5 meter tall leg kit (60 inches)", $5,800; "SSI Hydraulic Shredder Drive System", $40,500; "Screen maintenance assist system", $29,500. Total of above five items: $383,900.

   O&M cost: $72,270/year

   Explanation: The representative from SSI Shredding Systems provided a detailed O&M estimate of $6.60 per ton. The labor cost is integrated in the O&M cost estimate provided by SSI Shredding Systems.

   30 tons/day × 365 days/year × $6.60/ton = $72,270 per year.

3. Gasifier

   Capital cost: $5,635,000

   Explanation: "$4,900,000 plus taxes and freight", provided by Sherwood-Logan & Associates, Inc.; assuming taxes and freight are 15%,

   $4,900,000 × 15% = $735,000.

   $4,900,000 + $735,000 = $5,635,000.

   O&M cost: $236,284/year

   Explanation: The representative from Sherwood-Logan & Associates, Inc wrote, "Labor is $1.25 per MMBtu (assumes 1 operator per shift @ $50,000 per year)"; "Power $.14 per MMBtu"; "Maintenance $.46 per MMBtu". The gasifier processing 30 tons/day mixed MSW and C&D is assumed to produce 16.2 MMBtu/hr gross, 13 MMBtu/hr net, operating 7884 hours/year. Costs per year based on 16.2 MMBtu/hr and 7884 hours/year. Labor: $159,651/year. Power: $17,881/year. Maintenance: $58,752/year. Total O&M cost: $236,284/year.

4. Ash handling: **$10,950/year**

    Explanation: As per a discussion with our advisor Prof. Castaldi, we estimate that the total cost of ash handling, including on-site containment and transfer to an ash landfilling facility is estimated to cost on average $10/ton for non-hazardous waste ash. Assuming 10% of the weight of the mixed waste remains after gasification as an ash,

    ```
    30 tons/day × 10% = 3 tons/day ash.
    3 tons/day × 365 days/year = 1095 tons/year.
    $10/ton × 1095 tons/year = $10,950/year.
    ```

5. Producer gas storage tank: **$150,000**

    Explanation: This is a rough estimate based on similarly sized liquid fuel tanks found online.

6. Additional equipment (producer gas piping, gas composition monitoring, valves, flow meters, etc.): **$619,390**

    Explanation: This assumes the total cost of additional equipment listed will be 10% of the subtotal of **Table 7**, "Estimated Costs of Proposed Waste to Energy Gasification Project at BNY."

7. Engineering design, legal services, permitting, and incidentals: **$1,238,780**

    Explanation: This assumes the total cost of engineering design (including but not limited to fluid mechanics design for gas flow in pipes and sizing and pressurization of the producer gas storage tank), legal services, permitting, and incidentals will be 20% of the subtotal of **Table 7**, "Estimated Costs of Proposed Waste to Energy Gasification Project at BNY."

<u>Existing Estimated Costs at the BNY</u>

Estimated current cost of natural gas purchased by BNY Cogen: **$109,126,558/year**

Explanation: BNY Cogen did not disclose its natural gas supply charges but its natural gas costs are estimated using U.S. Energy Information Administration (EIA) data available online (U.S. Energy Information Administration, 2015). The EIA publishes annually natural gas average prices by state for electric power producers. The average price paid by independent electric power producers in NYS over the past five years (2010-2014) was $5.20

per MMBtu. The energy in the Cogen plant natural gas stream is 2,395.65 MMBtu/hr **(see Appendix E).** The estimated annual cost of natural gas by BNY Cogen is therefore

$5.20 × 2,395.65 MMBtu/hr × 8760 hours/year = $109,126,558.

Estimated current waste carting costs: **$5,750/day ($2,098,750/year)**

Explanation: Commercial waste is collected by private companies in NYC (as opposed to residential waste, which is collected by NYC Department of Sanitation). The New York City Business Integrity Commission (BIC) sets maximum rates that licensed waste carting companies can charge commercial customers for MSW collection. Carting companies and their customers can negotiate collection rates. The maximum cost is $11.98 per 100 pounds of waste (by weight), or $18.27 per cubic yard of loose refuse (by volume) (Business and Integrity Commission, n.d.). There is no such maximum rate limit for C&D collection. The following assumptions are made: the cost is calculated by weight, C&D is collected at MSW rates, and the BNY businesses pay 20% less than maximum allowable cost (assuming some economy of scale in collection costs), or $9.58 per 100 pounds. At 30 tons/day of total waste, the cost of collection is estimated at $5,750/day.

<u>Proposed Cost Savings to Companies in the BNY</u>

The gasification project provides the following savings to the BNY tenants and to the BNY Cogen plant. The following savings are also summarized in **Table 8.**

Savings to BNY Cogen for natural gas: **$327,974/year**

Explanation: Assuming the proposed WtE system provides BNY Cogen with producer gas at a greatly under market gas supply rate of $2/MMBtu (as opposed to a five year average of $5.20 for independent power producers in NYS), and using 13 MMBtu/hr as the producer gas energy rate (provided by Sherwood-Logan & Associates), the annual producer gas cost to BNY Cogen would be

$2/MMBtu × 13 MMBtu/hr × 7884 hours/year = $204,984/year.

The cost of the 13 MMBtu/hr at $5.20/MMBtu for 7884 hours/year would have been $532,958/year. Therefore, the annual savings to BNY Cogen would be

$$\$532{,}958 - \$204{,}984 = \$327{,}974.$$

Savings in waste carting costs: **$1,049,375/year**

Explanation: Assuming the proposed WtE system accepts MSW and C&D waste from the Yard at 50% of the cost charged by the carting companies ($5,750/day assumed current carting cost), $2,875/day ($1,049,375/year) will be saved.

	Current Annual Cost	**Annual Cost After Gasification**	**Annual Savings**
BNY Cogen Natural Gas	$109,126,558	$108,798,584	$327,974
BNY Tenants Waste Carting	$2,098,750	$1,049,375	$1,049,375
Total	**$111,225,308**	**$109,847,959**	**$1,377,349**

Table 8: Annual Total Savings to Companies in the BNY (Source: The authors)

Environmental Benefits Not Quantified

- Reduced number of trucks in surrounding neighborhoods and on highways carting waste from the BNY to waste transfer stations resulting in fewer transportation-related GHG emissions, less noise, less respiratory health issues associated with diesel emissions
- Savings in distant landfill/disposal fees
- Savings in GHGs from waste in landfills

Impact on Brooklyn Navy Yard Energy Independence

The Senior Director of Utilities at BNYDC provided the BNY electrical consumption and demand quantities for 2014 **(see Appendix C)**. We will compare the amount of energy produced by the gasifier with the 2014 BNY electrical consumption of 35,594 MWh. We will convert MWh to MW by assuming the electricity is supplied 24 hours/day, 365 days/year. Therefore, the electrical energy (consumption) of the BNY is

$$35{,}594 \text{ MWh} \div (24 \text{ hours/day} \times 365 \text{ days/year}) = 4.06 \text{ MW} = 4{,}060 \text{ kW}.$$

1 Btu/hr = 0.00029307107 kW. For simplicity we calculated that the effective energy of the producer gas (after considering the gross turbine efficiency of 34.3%) is 4.5 MMBtu. Using the

equivalence 1 Btu/hr = 0.00029307107 kW, 4.5 MMBTu/hr converts to 1,319 kW, which is approximately ⅓ of the electrical consumption used by the BNY. The actual benefit to the Yard is higher though, since some of the waste heat from the gas turbine is reused to generate the steam which is used throughout the yard for heating and hot water. We do not have steam usage data for the BNY.

6.6. Funding and Project Payback

We propose two general funding schemes: creating a new separate company to completely fund the gasification system and all its components (*Option 1*); or including current stakeholders in funding in exchange for free energy and/or waste collection from the gasifier (*Option 2*).

In *Option 1*, the new company will offer reduced waste carting costs to BNY tenants and reduced gas costs to the BNY Cogen plant as shown in **Table 8**. The new company will either seek grants for a loan down payment, or will enter into a power purchase agreement to pay for the equipment, installation, permitting, etc.

In *Option 2*, the gasification system will be cooperatively owned by the BNYDC, BNY tenants, and the BNY Cogen facility. The Cooperative will determine initial funding contributions and ongoing payments based on the amount of savings the gasification system will offer. For example, the cost savings to the BNYDC and the BNY tenants will be greater because the waste collection savings are expected to be larger than the gas cost savings to the BNY Cogen plant.

The project may qualify for renewable energy programs offering tax credits or rebates. The reinstatement of the Renewable Electricity Production Tax Credit (PTC), which expired on 12/31/2014, has been proposed in the President's Budget for fiscal year 2016. If the PTC is reinstated, the tax credit will be "made refundable" in the amount of 1.1 cents/kWh (Department of the Treasury, 2015). If the PTC is extended, the facility may qualify for up to $114,389.

$$4.5 \text{ MMBtu/hr} = 1{,}319 \text{ kW.}$$

$$1{,}319 \text{ kW} \times 7884 \text{ hours operation} = 10{,}398{,}996 \text{ kWh.}$$

$$30{,}030{,}156 \text{ kWh} \times 0.011 \text{ \$/kWh} = \$114.389.$$

The New York State Energy Research and Development Authority (NYSERDA) offers funding of unspecified amounts to approved renewable energy projects. The project must apply for the various programs available at the time (NYSERDA, 2015, November 24). One NYSERDA funding opportunity may be the "Clean Power Tech Innovation" program (NYSERDA, 2015, November 4). Another gasification project in the U.S. utilizing a PHG gasifier similar to what we proposed at BNY, the WtE plant currently under construction in Lebanon, Tennessee was eligible for multiple subsidies through state and national programs. The Lebanon plant received a grant of \$250,000 from the Tennessee Department of Environment and Conservation. In addition, 70% of the \$3.5 million project's interest was financed through a subsidy from the Federal Qualified Energy Conservation Bonds (QECB) program. ("Lebanon Breaks Ground on Waste-to-energy Plant", 2015). The QECB program was authorized by the U.S. Congress in 2009. The total funding available nationally was \$3.2 billion. Each state has been allotted a certain amount of funding to spend on qualifying energy projects in cities with large populations (greater than 100,000 people) (Energy Programs Consortium, 2013). Most of the QECB funds allotted to NYS have remained unspent: by October 2013, \$172,730,130 of the \$202,200,000 reserved for NYS projects is still available (Energy Programs Consortium, 2013). Assuming a loan term of 10 years, 8% simple interest, and 10% (\$805,207) down payment, the QEMS subsidy of 70% of the interest on the loan would be \$2,790,000.

Using the calculated total project capital cost of \$8,052,070 **(see Table 7)** and total annual savings of \$1,377,349 **(see Table 8)** to the companies in the BNY due to reduced carting costs and reduced natural gas costs, the simple payback period is 5.8 years.

$$\$8,052,070 \div \$1,277,349 = 5.8$$

The federal and state subsidies outlined would reduce the project payback time.

6.7. Siting

Since the WtE facility at the Yard will provide its producer gas to BNY Cogen, close proximity to the cogeneration plant is ideal. During the tour of the BNY with the former BNYDC VP of Maintenance, we saw that Dock 72 is adjacent to the cogen plant. We were advised that siting the

WtE on Dock 72 would allow pipes to be placed directly from the WtE facility to the cogeneration plant.

In July 2015, news articles were published expressing developers' intentions to build a 675,000 ft^2 building on Dock 72 for a co-working company called WeWork Companies Inc. ("A New Office Building", 2015). Given that our desired location is reserved for another use, an alternate site is likely necessary. Since the WtE facility will have a relatively small footprint (gasifier: 60 ft x60 ft, shed footprint: 30 ft x 60 ft, producer gas storage tank: 13.12 ft (4m) dia. x 32.81 ft (10m) high), and since there are currently other vacant waterfront areas in the Yard (and Admiral's Row is also being redeveloped), this project assumes that another suitable location within the BNY will be found. (For reference, the BNY Cogen building footprint is approx. 220 ft x 200 ft (measured with Google Earth) and a standard block in Manhattan is around 200 ft x 800 ft.)

In an email dated Dec. 16, 2015, the Projects General Manager of Power Plant Management Services, LLC suggested another location that may work: Dry Dock 4, to the west of Dry Dock 2 and just to the north of the BNY Cogen plant. An additional site visit would confirm sufficient space availability. The close proximity of Dry Dock 4 to the BNY Cogen plant would allow direct piping from the gas storage tank to the cogen plant. If a more distant site is chosen, periodic gas transport by truck within the Yard may be necessary.

6.8. Study Limitations and Assumptions

The Brooklyn Navy Yard is a large campus with over 330 tenants in many industries. Because of the time constraints of this project, waste flows at BNY were approximated through a dumpster count. Before building an actual physical WtE system for BNY, however, an accurate survey of waste production per tenant would need to be completed because the waste composition of the feedstock affects the heating value of the producer gas created. It would also be advantageous to survey the tenants regarding their actual waste collection contracts to more precisely determine how much money they would save by utilizing the garbage on-site rather than having the garbage carted to waste processing facilities.

Calculations in this project have been based on varying heating values: the gasifier energy output provided by Sherwood-Logan & Associates, Inc. is based on heating values which differ from the heating values we calculated based on the assumed gas compositions of the producer gas produced from a 50:50 mix of MSW and C&D. The calculations done in this project, however, are sufficient for estimation and feasibility purposes.

BNY renovations and new construction also add uncertainty to the amount of waste available for the WtE facility. Because BNY is a successful urban industrial park, it attracts new tenants. The expansion of the BNY, as described earlier in this report, will affect the BNY waste stream quantity and composition. The future BNY waste stream will likely increase significantly from our estimated 30 tpd, possibly doubling, depending on the types of tenants that sign on to the new developments.

6.9. Social and Environmental Issues

There are several contentious issues with siting a waste to energy facility in a dense urban area. Emissions from the thermal treatment of the waste is the largest issue to be resolved. In this project, we will be building a system that closely pairs with the existing cogeneration power plant at the Yard. The plant was operated by the Navy as a coal fired power plant before it was converted to a natural gas fired plant. With the history of the power plant, the local population is already accustomed to this facility being in their neighborhood. Based on our initial emissions calculations, we do not believe our proposed gasification plant will create measurable additional emissions. A more in-depth emissions analysis should be conducted during the project planning stage if this project were to be initiated.

The other issue with emissions to note is that by treating waste within the BNY we will reduce the number of garbage trucks leaving the Yard, which would reduce truck exhaust emissions and also would reduce traffic on neighborhood roads. As we discussed earlier, the large majority (68%) of NYC's waste is transported long distances to landfills, mostly to Pennsylvania, Ohio, Virginia, and New Jersey. Much of this waste is transported via trucks which amounts to approximately 1,783,574 tons of waste per year traveling over 40 million miles, and producing an average of 0.03 metric tons of GHGs per ton of waste, totaling approximately 53,500 metric tons of GHGs (Gamerman, 2012). Gasifying a portion of this waste for the production of electricity will save considerable amounts of these GHGs from entering our atmosphere.

We estimated that the Yard generates approximately 30 tons of trash per day, or 150 tons per week based on a 5 day work week. Garbage trucks of the size that service our city have a capacity of 12.5 tons each, so gasifying 30 tons per week of waste would save approximately 12 truck round trips per day, amounting to 60 round trips per week (Kellermann & Gamerman, 2014). Using the average estimate of 0.03 metric tons of GHGs per ton of waste, the reduction of trucks will save approximately 225 metric tons per year. Also, with the waste stream expected to increase due to new developments ongoing and proposed at the Yard, the number of trucks will likely increase to 24-30 per day.

In the EU, many cities have their WtE facilities located within city limits. This reduces the need to truck waste long distances, and many of the facilities are also CHP and provide district heating. Cites throughout Denmark, Norway, and Sweden are examples of this (CEWEP, 2014). Locally we have combustion plants located in higher population areas in Hempstead, Long Island, and in Essex County, NJ. While these are combustion plants, they are local examples that siting WtE in denser urban areas can be done.

Historically, landfills and waste transfer stations have been located in lower income areas and in industrial areas that have access to waterways. The Yard is no exception to this, with a fairly dense residential neighborhood just outside of the its borders. However, the residential landscape of Brooklyn is undergoing significant changes and the neighborhoods surrounding the Yard are seeing an influx of new higher income "luxury" developments and increases in resident populations. It will be important to demonstrate that the new gasification process will not have an increased negative environmental or human health impact to the Yard neighborhood residents, new and old. If the project is initiated, it will be designed to perform at or better than EPA standards for emissions. It will be important to communicate the gasification system's safety measures and emissions controls to the community.

In addition to concerns about emissions, another concern for area residents regarding the WtE plant likely would be over the potential odors in the Yard. If the gasifier or shredder needs maintenance or repair some waste will be piled while it waits for processing. Though this amount would likely not exceed two days worth of trash, or 60 tons, and would be processed rather quickly, controls will need to be put in place to remediate this concern. A simple method would be to build a shed where the waste stockpile can be contained and where the shredding pre-treatment can take place. The shed should be designed with passive ventilation strategies that will draw air upward and through filters to reduce odors and will not require energy inputs.

A primary function of implementing WtE at the Yard is to reduce the volume of trash sent to a landfill, and will need to consider how to deal with the waste ash after gasification. Though the final volume will be reduced to about 10% of initial trash volume, or about 3 tons per day. If we base the volume calculation on a 5 day work week, or yearly average of 22 working days per month, we would generate about 66 tons per month. (As opposed to 660 tons per month of untreated waste). The waste ash is commonly used as a cover for trash in landfills, thus we propose that disposal of the ash can be sent from the Yard by barge to one of the existing transfer stations in NYC. There is a potential to use the heavier ash product as an aggregate for concrete construction, but with the ash containing metals and minerals, toxicity is a concern and the ash may need further treatment for its use in concrete. This is beyond the scope of this project, but is a consideration for future research.

6.10. Stakeholder Analysis

When the project is initiated an in-depth stakeholder analysis should be conducted to determine who the stakeholders are, what their role is in the project, how they impact and are impacted by the project, and based on that information, how and when should they be communicated with. We predict that the five key stakeholder groups for building a gasification facility at the BNY are the BNY business owners, BNY employees, BNYDC, BNY Cogen plant managers and residents from the surrounding neighborhoods. These stakeholders should receive regular status reports on the project, as well as have the opportunity to voice their opinions before key decisions are finalized. In addition to the five key groups, there are a number of other groups that must be considered and kept current on developments, as well as given an opportunity to participate in planning, and to contribute their expertise and opinion. The additional stakeholders to include are: ConEd, DSNY, EPA, the Mayor of NYC, the Mayor's Office of Sustainability, New York City Department of Environmental Protection (DEP), New York State Department of Environmental Conservation (DEC), PHG Energy, SSI Shredding Systems, and waste haulers. Proceedings should be transparent, posted in advance and accessible to the public in order to provide an environment of trust and to foster participation. The in-depth stakeholder analysis will determine if additional groups should be included as well as specifying who exactly within the groups will be the leader or representative on their group's behalf.

7. Recommendation and Conclusion

Small-scale localized gasification should be implemented as a sustainable solution for the portion of the waste stream that can not be reasonably reused, recycled or organically treated, in order to comply with the waste and GHG reduction goals of *OneNYC*. Small-scale waste to energy gasification at the Brooklyn Navy yard is a viable and sustainable alternative to landfill disposal. New York City's current sustainability plan – *OneNYC* – under Mayor Bill de Blasio sets the "0x30" goal to completely eliminate landfills as a waste disposal method by the year 2030. This zero waste goal is achievable with appropriate planning for the variety of waste streams in our city. Organics should be processed for energy capture or to produce a soil additive to add nutrients and improve soil fertility. All materials that are recyclable should be collected and recycled. Additionally, policies must be implemented that improve upon current recycling laws and mandates. Producer responsibility is one avenue towards improving the afterlife of a formerly discarded object. By making the producer responsible for how their products are disposed of, the burden on government decreases and is instead shouldered by businesses in a competitive landscape. For that remaining portion of the waste stream that is not naturally compostable, and is not currently part of a city's recycling program, a disposal method must be selected that causes the least harm environmentally, financially and socially. As we've outlined in this report, small-scale gasification performs well on all three aspects of sustainability's triple bottom line. Our proposed system improves quality of life for the community and it is a realistic investment with a payback period of under six years. Further research would determine the feasibility of this project and to determine if modifications must be made and in what capacity. Most critically, a waste characterization study must be undertaken so that the solution we've proposed can be more accurately vetted.

8. Areas for Future Research

Waste Characterization

In order to maximize the operational efficiency of the gasification equipment, it is critical to have an accurate estimation of the composition of the feedstock. We did not have the authority or access to conduct an in-depth analysis of the waste characterization and disposal at the Yard. We were able to figure an estimated amount of waste generated at the Yard from observations during an afternoon tour. However, this was an informal tour and did not grant us full access to all waste generated at the Yard. We suggest that the BNYDC supports an in-depth analysis in order to determine exactly how much as well as the type of waste that is generated (e.g. organics, MSW, C&D, etc.), in addition to how that waste changes over time and how it might change in the foreseeable future. The results of the analysis could help prove which type of WtE system would be best suited for the conditions at the Yard and also allow for the designing of a system that is optimized to the precise requirements at the site. This is especially critical considering the growth of organics at the Yard (from e.g. distillery, rooftop vineyard, rooftop garden) as well as the scale of development that has been announced during the period of our research that is yet to be completed (e.g. Wegman's grocery store opening 2017, WeWork building, Building 77).

Scalability

Could the environmental impact of waste disposal from the surrounding neighborhoods (e.g. Fort Greene, DUMBO, downtown Brooklyn, Clinton Hill, etc.) be reduced if the portion of non-recyclable, non-compostable waste was gasified locally instead of taken to a transfer station where it's then hauled to a distant landfill? We suggest further research into implementing a small- to medium-sized gasification solution to process waste from the surrounding areas in order to determine if it would be feasible, sustainable, and on what scale and in what exact locations it could work. The analysis would have to include a thorough investigation into the air quality and subsequent health impacts on the residents of the neighborhoods. Although there is a current issue in NYC of concentrated waste transfer in the Bronx, that issue should not be offset by merely transferring the imbalance to a different area. The residents of the neighborhood should not experience a degradation in air quality or other health and safety effects. Ideally, considering there are many negative affects from hauling waste via truck and disposing of it in landfill, the aim is that the impact from a local WtE solution would have a smaller ecological footprint than does long distance landfill disposal.

Adaptability

Is small- to medium-scale gasification adaptable to similar sites, especially revitalized industrial park zones? The technological solution that we used in our project is scalable and can process a wide variety of materials. The exact waste characterization and site requirements will determine what is feasible, but we recommend further research into standardizing the process for designing a thermal WtE solution for similar sites. Brooklyn Army Terminal in Sunset Park is suggested as a potential site for a localized gasification solution. A waste characterization study must be conducted to determine which type of system would function best based on their conditions. Additionally, without the presence of a cogeneration facility, the type and specifications of the WtE solution will likely need to be adapted, especially transportation of the producer gas.

Pneumatic Tubes

Lastly, we suggest research into pneumatic tubes as a safer and more environmentally-friendly method for transporting waste. In locations with established and embedded infrastructure this solution may be too costly and disruptive to implement depending on the underground conditions of the site in question. For new development areas, however, installing pneumatic tubes is more feasible since there are no legacy systems to integrate with or to obstruct the construction process. Pneumatic tubes are used in an area outside of Paris to transport non-recyclable waste to a thermal WtE facility (Desai, 2015). Roosevelt Island in NYC also uses pneumatic tubes to compact and decrease the volume of the waste and therefore trucking demands, which saves on emissions and related dangers, as well as provides a cleaner solution that eliminates above ground odor and rodent issues (Chaban, 2015).

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Appendices:

A. **Brooklyn Navy Yard Visitor Map**
B. **Air Title V Facility Permit for Brooklyn Navy Yard Cogeneration Plant (Page 1)**
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D. **Brooklyn Navy Yard Site Visit: Dumpster Count, April 18,2015**
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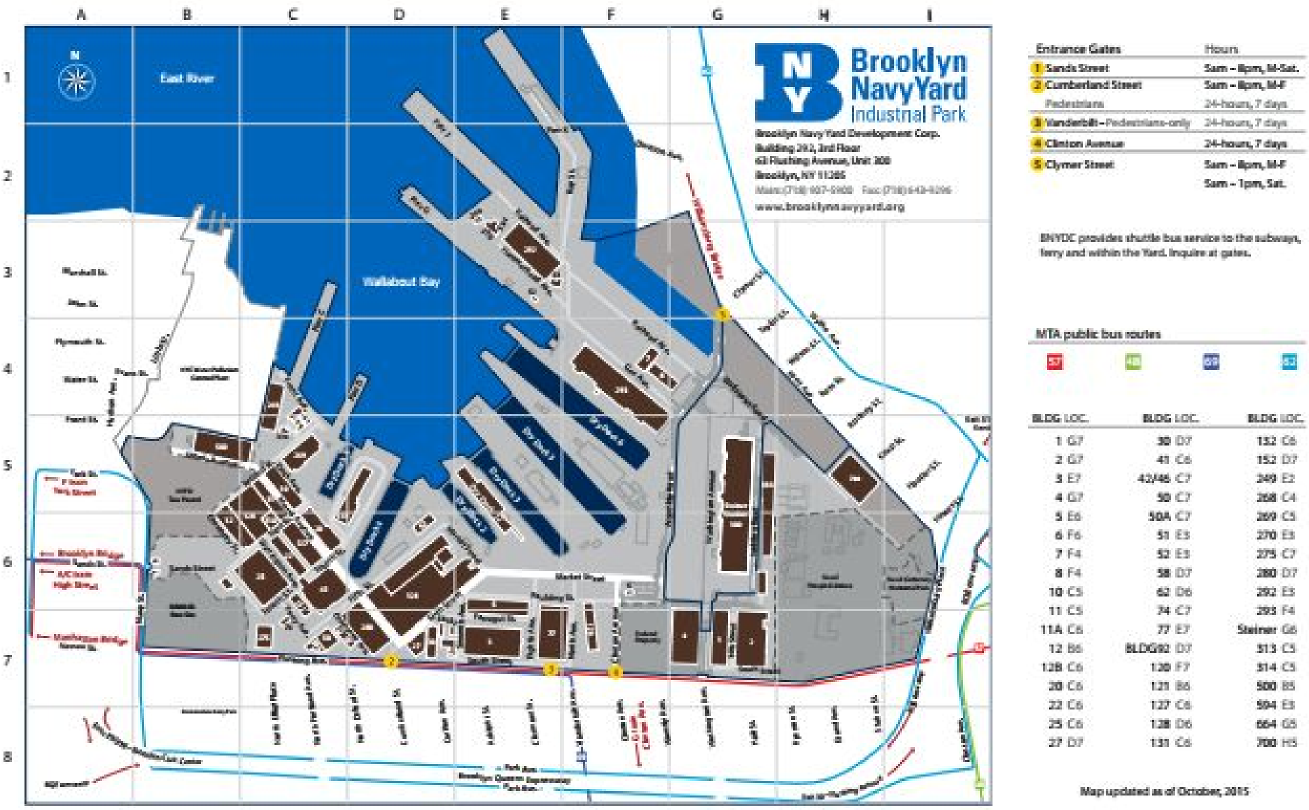
F. **Photos from Site Visits**

Appendix A: Brooklyn Navy Yard Visitor Map



(Source: BNYDC, November, 2015)
http://brooklynnavyyard.org/media/uploads/BNYVisitorMap.pdf

Dry Dock 72 was added to the map in late 2015, after we obtained maps during our initial site visit in April 2015.

Appendix B: Air Title V Facility Permit for Brooklyn Navy Yard Cogeneration Plant, page 1

New York State Department of Environmental Conservation
Facility DEC ID: 2610100185

PERMIT
Under the Environmental Conservation Law (ECL)

IDENTIFICATION INFORMATION

Permit Type: Air Title V Facility
Permit ID: 2-6101-00185/00008
Mod 0 Effective Date: 01/04/2013 Expiration Date: 01/03/2018

Mod 1 Effective Date: 03/16/2015 Expiration Date: 01/03/2018

Permit Issued To:BROOKLYN NAVY YARD COGENERATION PARTNERS
63 FLUSHING AVE UNIT 234
BROOKLYN, NY 11205-1074

Contact: CHRISTOPHER TRABOLD
BROOKLYN NAVY YARD COGENERATION PARTNERS
63 FLUSHING AVE, BLDG 41 UNIT #234
BROOKLYN, NY 11205
(718) 237-6755

Facility: BROOKLYN NAVY YARD COGENERATION PLANT
63 FLUSHING AVE|BROOKLYN NAVY YARD, BLDG 41 UNIT #234
BROOKLYN, NY 11205

Contact: CHRISTOPHER TRABOLD
BROOKLYN NAVY YARD COGENERATION PARTNERS
63 FLUSHING AVE, BLDG 41 UNIT #234
BROOKLYN, NY 11205
(718) 237-6755

Description:
This facility **(Brooklyn Navy Yard Cogeneration Plant)** is a 286-megawatt (MW) gas-fired power plant. The plant consists of two Siemens V84.2 gas turbines, each equipped with a Heat Recovery Steam Generator. Gas Turbine air inlet cooling technology may be installed and operated at the plant on each of the combustion turbines. In addition, two distillate oil-fired emergency generators are provided. The plant supplies electricity to Con Edison and the Navy Yard, and supplies steam to Con Edison, the Navy Yard, and the Red Hook Water Pollution Control Plant.

Original Renewal 2 Mod 0 Title V permit was issued on 1/4/2013 and would expire on 1/3/2018. This permit modification is for the installation of Siemens Si3D Thermal Performance Upgrade that improves plant thermal efficiency and reduces plant emissions on a per megawatt-hour basis. The changes do not impact the short-term and annual permit limits.

DEC Permit Conditions
Renewal 2/Mod 1/FINAL

Page 1

Full document located online:
http://www.dec.ny.gov/dardata/boss/afs/permits/261010018500008_r2.pdf

Appendix C: Brooklyn Navy Yard Electrical Consumption & Demand, 2014

Brooklyn Navy Yard Electrical Consumption & Demand, 2014		
Month	Consumption (MWh)	Demand (kW)
Jan-2014	3,210	7,022
Feb-2014	2,968	6,882
Mar-2014	3,039	6,720
Apr-2014	2,822	6,720
May-2014	2,749	6,420
Jun-2014	2,990	7,336
Jul-2014	3,242	7,706
Aug-2014	3,013	7,164
Sep-2014	2,784	7,315
Oct-2014	2,660	6,087
Nov-2014	2,946	6,577
Dec-2014	3,171	6,296
TOTAL	**35,594**	**75,825**

(Source: Compiled by the authors from info from the Senior Director of Utilities, BNYDC, 2015)

As explained by the Power Plant Management Services, LLC Projects General Manager: The demand of 7,022 is measured in kW and represents the highest 15 minute load BNYDC consumed. Large consumers get billed for their consumption (kWh or MWh) and separately for the peak demand (kW or kWd) they put on the system. Another way to look at it is 6,000 KW for one hour is 6,000 kWh or 6 MWh. Two hours at that demand would be 12,000 kWh or 12 MWh. (1 MWh = 1000 kWh)

Appendix D: Brooklyn Navy Yard Site Visit: Dumpster Count, April 18,2015

Brooklyn Navy Yard - Site Visit - Saturday April 18, 2015 - Dumpster Count					
Building Number	Erin's Count		Sarah's Count		Building/waste description
	Dumpster size (yd3)	# of times emptied per week	Dumpster size (yd3)	# of times emptied per week	
N/A	30	1	30	3	Public trashcans, common building restrooms, hallways, entrances
275	24	2	22.5	3	Mixed tenant building
132	20	1			Company builds interiors, custom woodwork for restarants, etc.
50A	4	2	4	2	Sprinkler company
50	20	1	20	1	
74	4	1	4	1	Drycleaner
42-46	20	1	20	1	Duggal. Filco Carting (Bic # 390). 20yd is a compactor.
280	30	1	30	1	Saturday Night Live set building, scenery
280	25.5	0.415	25.5	2.5	Small dumpsters, emptied every 2-3 weeks. Sarah wrote that the 25.5 yarder is picked up 2-3x/wk, Erin wrote pick up is every 2-3 weeks. Erin's note makes more sense.
127	30	3	30	3	Sweet n Low. Sweet n Low as multiple buildings.
131	13	1	15	1	Mixed tenant building
N/A	60	1	60	?	Various construction projects. SB didn't note frequency of pick up.
10	20	1	20	1	Duggal. 20yd is a compactor.
N/A			20	0.25	Christian's 20 yarder for scrap metal.
269	10	2			Agger Fish is in buildings 269, 313
249			1.5	1	
269			0	0	Just a warehouse. Usually used as a prep place for bldg 268. Used for shoots.
313			10	2	Agger fish. Erin has this as bldg 269. I have bldg 269 as a warehouse for bldg 268.
268	30	0.25	30	0.25	Event space, the 30yd dumpster is emptied 1x/month
500	34	1	38	1	Duggal. SB noted: 30yd 1x/wk + 4yd 2x/wk.
11, 12, 12B	60	0.5			Big warehouse, mostly stone by-product, emptied every 2 weeks
12			60	0.5	Ice Stone. Erin noted this differently. I'm assuming those 60yds were just for icestone but she noted that it's for 3 buildings (11, 12, 12B). Some portion of this waste is probably stone byproduct and is not useable as feedstock for gasification.
27	1	1			Small tenants building
30	4.5	1	3.5	1	Small tenants building
152	1	1	1	1	Single tenant, electric motorcycles
92	2	1	2	1	The Brooklyn Navy Yard Center at BLDG 92 is an exhibition, visitors and employment center that is operated as a program of the Brooklyn Navy Yard Development Corporation (BNYDC).
3	60	1			Multi-tenant, single waste contract, huge warehouse spaces
62	3	1	3	1	
5	20	1	20	1	Printing company, woodworking. Waste is paper, wood. Lots of 1-yard dumpsters adding up to 20yd.
120	20	1	16	2	New York Decks, wood scraps
293	80	2			FC Modular. 1-20yd is a compactor. SB NOTE: I entered this info as 2 separate lines since the compactor is a different weight.
293			60	2	Forest City (FC) Modular. Units for Barclays apartments.
293			20	1	Forest City (FC) Modular. Units for Barclays apartments. 20 yarder is a compactor.

292	20	0.4	20	2	Scrap metal. SB noted: 4 5yarders 2x/wk. Bldg 292 houses BNYDC among others. BNYDC is the non-profit corporation that manages the Brooklyn Navy Yard on behalf of its owner, the City of New York. Other tenants: med waste (haz mat) incinerated somewhere.
292	10	1	10	1	10-yd is a compactor
292	80	2	60	2	Various waste. SB noted 2 30yds 2x/wk.
121			?	3	Kings County Distillery. Action Carting. They have a lot of organic waste and they compost + sell to a ?pig? farm?.
128			0	0	Green manufacturing. No tenants till end of year. Robotics, clothing, Brooklyn Roasters. A lot of the tenants from the yard will relocate there.
Totals					
Total (yd3/week)=	**915**		**902**		
Total (yd3/month)=	**3,658**		**3,607**		
Total lbs/month (500 lbs/yd3)=	**1,829,165**		**1,803,500**		
Total tons/month (2,000lbs/ton)=	**914.58**		**901.75**		
Total metric tons/month (1,000kg/mton)=	**829.69**		**818.05**		
Total metric tons/day (30 days/mo)=	**28**		**27**		
Additional Notes					
3 big multi-tenant buildings.					
Pilot recycling program					
Pallets picked up every Wednesday by a carter.					
Duggal new HQ on site.					
Need to convert compactor volume to dumpster volume (b/c compactor has higher weight than dumpster).					
Cogen plant provides steam (heat) to the majority of the yard.					
GMD does the ship work. They have a special setup (contract) similar to Steiner, in that within their boundaries they are mostly? self contained. Not sure what that all specifically means.					
Add? Bldg#2/Capsys? What about Steiner? I thought I counted dumpsters but I don't know if already added that here.					

(Source: The authors)

Appendix E: Brooklyn Navy Yard Cogeneration Gas Burn, 2014-2015
(Source: compiled by the authors with data from the Projects General Manager at Power Plant Management Services, LLC)

All Readings Included	
Year	**Dth**
2014	2,177.58
2015	1,998.64
Average	**2,088.11**

Zero Value Readings Excluded	
Year	**Dth**
2014	2,290.22
2015	2,501.08
Average	**2,395.65**

Appendix F: Photos from 4 Site Visits (Source: the authors)

1. *Newtown Creek Wastewater Treatment Plant Tour* (February 28, 2015)

Digester Eggs

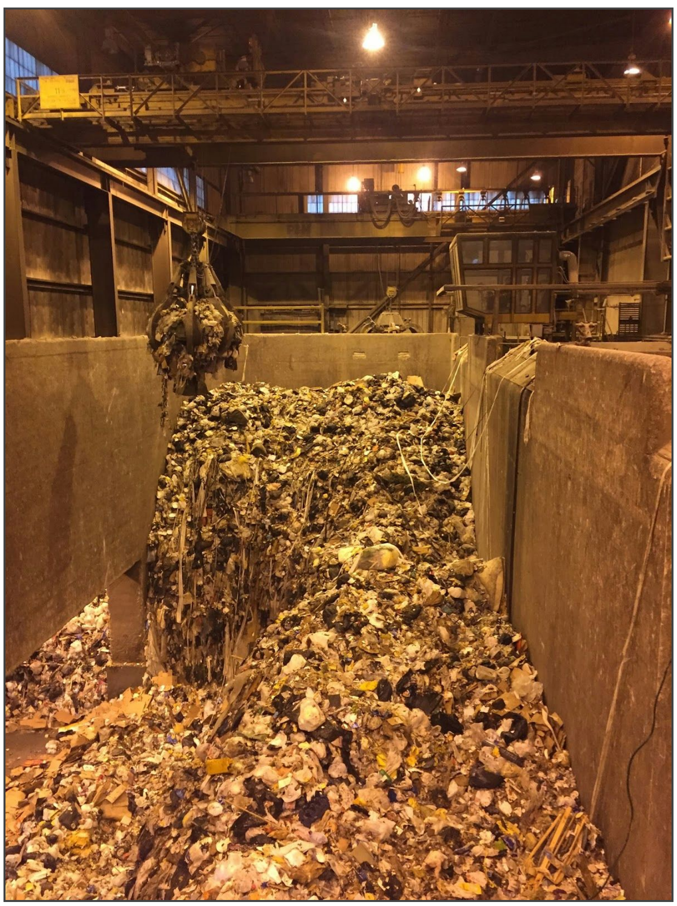
Methane Flaring

Treatment Ponds, View from Top of Digester Eggs

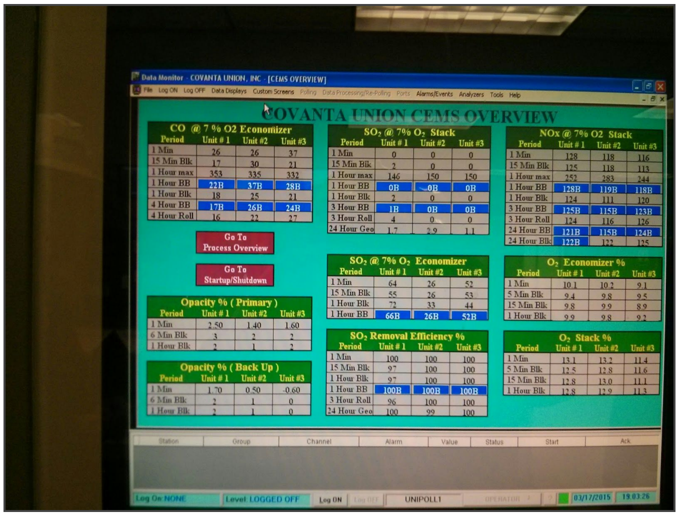
Treatment Ponds

2. *Covanta Energy Combustion Waste to Energy Union Facility Tour*, led by Todd Frace, Chief Engineer, Covanta Energy (March 17, 2015)

Tipping Floor



Waste Mixing Area

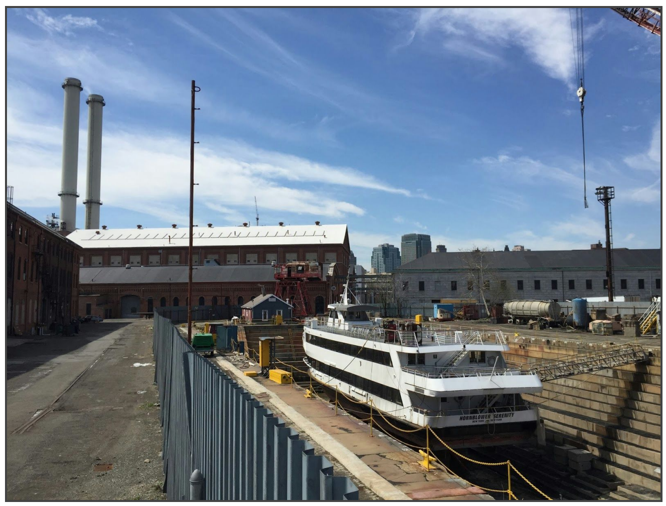


Continuous Emissions Monitoring System (CEMS) Overview Screen

3. *Brooklyn Navy Yard Tour*, led by Christian Miller, former VP of Maintenance, BNYDC (April 18, 2015)

BNY Cogeneration Facility

Building 128, Green Manufacturing Center



Ship Repair Dock

Modular Construction Manufacturing Site (FC Modular)

Pipes for Steam Distribution

Rooftop Wind Turbines

Dumpster Counting

Red Hook Wastewater Treatment Plant

4. *Brooklyn Navy Yard Cogeneration Plant Tour*, led by Chris Trabold, Projects General Manager, Power Plant Management Services, LLC, Brooklyn Navy Yard Cogeneration Project (May 13, 2015)

View of the Yard from Rooftop of Cogen Plant

View of Docks and Piers from Rooftop of Cogen Plant