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FINAL REPORT

Advanced Bioreactor Recycling System for Producing Energy and SNG

EISG AWARDEE

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Acknowledgement Page

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Abstract

The goal of this project was to determine the feasibility of generating energy and methane from an advanced anaerobic bioreactor. Here, methane would be produced not only from landfill gas but also from recovering the remaining landfill material. In this study, samples were collected from bioreactor cells at the Yolo County Central Landfill in Woodland, California. The 12-year old degraded waste was excavated, characterized, categorized, and analyzed. In the larger-size fractions of the excavated waste, combustibles were 79% for the anaerobic cells. These fractions had a calculated energy potential of approximately 8 MJ per kg of total dry waste. This included the parts of the wood, paper, cardboard, plastics, and textiles, that were easily identifiable. The fines were 46w% in the anaerobic cells which had an average combustible fraction of 17w% on a dry basis. Analysis of the fines indicated biomass-type materials and confirmed suitability for gasification. If the finer fractions could be efficiently separated into combustibles and non-combustibles, another 1 MJ per kg of total dry waste could be recovered. While the project findings support the technical feasibility of the concept, some objectives such as energy content and costs did not reach the anticipated targets. Additional costs arise from excavation, drying, separation, and gas cleanup. These costs could be offset by gains made on recycled materials, savings on costs related to feedstock, recovered landfill space, landfill construction and operation, and landfill post-closure. Other environmental and societal benefits may also add to the attractiveness of the concept despite the higher cost for SNG compared to fossil natural gas.

Key Words: (landfill mining, anaerobic bioreactor, waste gasification, landfill digestate)

Executive Summary

Introduction

In order to meet the mandated Renewables Portfolio Standard, California will need to generate some of its natural gas from renewable sources. One possible method is to use an Advanced Bioreactor Recycling System and generate SNG (Synthetic Natural Gas) from landfill gas and from the digested waste. This also has the potential to reduce landfill space and therefore help California in managing its waste problem. During this study, digested landfill waste was mined from an anaerobic bioreactor at the Yolo County Central Landfill. The composition and energy contents were evaluated and it was estimated how much it would cost to generate SNG through gasification and methanation.

Project Objectives

- Determine moisture, ash, and carbon content of at least one sample already collected from an aerobic (as opposed to anaerobic) bioreactor. Determine the final number and locations of samples to be collected from the anaerobic bioreactor. The objective is that one dried size fraction contains more than 15w% carbon.
- Collect at least 15 samples (5 different locations and 3 different depths) from Yolo County’s bioreactor landfill cells. Categorize each sample into at least 10 different material or size groups and report those. The objective is that at least 70% of the mass is readily screened through a 1" sieve.
- Report proximate, ultimate elemental, and energy content (e.g., moisture, fixed carbon, volatile matter, ash, C, H, N, O, S and certain trace elements) of at least 10 samples in percent. Report composition and toxicity of ash of at least 10 minerals. The objective is that one dried size fraction contains more than 20w% carbon. Further, that this fraction contains less than 1000 ppmw Cl and 0.1 ppmw Hg.
- Report performance of sample in gasification environment such as measurement of composition of gas and solid residues. Goal is to have melting point of residual ash to be higher than 1000 C.
- Estimate the total cost of methane per cubic foot and compare it with the market price for fossil and renewable natural gas. The objective is that methane will cost less than $15/MMBtu, and less than $5/MMBtu accounting for landfill cost savings.

Project Outcomes

- Analyses of the samples from the aerobic reactor were completed and found that the manually sorted fraction, the fine fraction, and moisture were 28w%, 32w%, and 40%, respectively. The combustibles in the fine fraction were 17.6w% on a dry basis, and the carbon content was estimated to be less than 10w%.

- Samples were collected from two anaerobic bioreactors and classified by size and material. The manually sorted fraction and the fine fraction were about equal in amount. The manually sorted fraction contained mostly paper, wood, cardboard, film and rigid plastics.
- The fine fractions from the anaerobic bioreactors were analyzed for composition and energy content. They contained 16w% combustibles (9w% carbon). The major inorganic elements were Si, Fe, Ca, Al, Na, Mg, K, and S. The content of Cl was 0.2w% and that of Hg was 0.18ppmw. The energy content of the mined sample was 9 MJ/kg in which the contribution of the manually sorted fraction was 8 MJ/kg and that of the fine fraction was 1 MJ/kg. The fine fraction was 90% biocarbon-based, while the manually sorted fraction contained larger amounts of petroleum based products.
- Several of the ground and weight-separated samples of the fine fraction were analyzed in a Thermo-Gravimetric Analyzer (TGA). The samples showed a large amount of volatiles to be released below 500 C. The ashes generated in both reducing and oxidizing atmospheres had melting points above 1000 C.
- Costs of a combined production of SNG were estimated to be $19.74/MMBtu. If only the landfill gas would be converted to SNG, the costs were estimated to be $7.66/MMBtu.

Conclusions

- In the aerobic bioreactor, the fine fraction contained less than 15w%. If the fine fraction is to be used efficiently for energy generation, separation into a light fraction can increase the percentage of combustibles.
- In the anaerobic bioreactors, the fine fraction was less than 70w% of the dry mass. Therefore, the manually sorted fraction should be included in an energy-conversion process.
- The fine fractions of the anaerobic bioreactors contained less than 20w% carbon, but a separation of a light fraction increased its carbon content to above 38w% (70w% combustibles). A reliable removal process of Hg is important, and S and Cl need to be removed during the process since they can impact the catalyst or cause corrosion.
- The fine fraction contains a large amount of volatiles, and the ash-melting temperature was high enough to make it suitable for gasification.
- The high capital and operating costs of gasification and SNG synthesis cause the per-Btu costs to be several times higher than for fossil natural gas. These processes would only be justified if the technologies are further improved, or if landfill volume reduction, energy security, and renewable energy become overriding factors.
- Creating electricity is expected to be less expensive than creating SNG due to a smaller number of conversion steps. In the mined landfill waste, the manually sorted fraction was 54% of the total dry mass and contained on average 27% paper and cardboard, 12% plastics, 8% wood, and 3% textiles. It represents the main value for energy generation but recycling of some of these materials may also be considered as an economic alternative.

Recommendations

- In order to determine if the ash from gasification could become Class II waste, conduct additional measurements on its toxicity and leachability.

- Investigate the heavy fraction of the fines further to determine additional extraction of combustibles as well as usability of this fraction as an alternative landfill daily cover.
- Investigate if the leachate could be used for separation of all the fines into light and heavy fractions.
- Characterize the plastic fractions in the manually sorted fraction as to type of plastics to determine the options of recycling or energetic use.
- Conduct additional core drilling into deeper sections of the bioreactors to confirm that the composition is uniform throughout the bioreactor.

Public Benefits to California

- Although production costs of SNG from mined landfill materials are currently not competitive with conventional natural gas, other benefits accrue including the potential to make SNG with a high level of renewability to help meet state goals for renewable energy and reduced greenhouse gas emissions both by direct reduction of landfill emissions and displacement of fossil sources. Potential credits for these added benefits could be investigated as a means of implementing integrated material recovery options on a commercial basis.
- Employing the production of SNG at the larger landfills could reduce the annually needed landfill capacity by 3 million tons of waste, equivalent to 4 million cubic yards (3 million cubic meters) in landfill volume. Cost savings to the public would exceed $30 million per year on externalities related to air and water pollution and land use.
- Indirect benefits from producing SNG from landfill gas and the degraded solid waste from a bioreactor include both increased employment and improved energy security from use of local resources. They also derive from reduced landfill volumes and land recovery allowing other developments to occur with additional socioeconomic effects.

Introduction

California imports 90% of its natural gas and it has also passed legislation supporting a Renewables Portfolio Standard requiring electricity retailers to achieve a goal of 33% renewables by 2020. Therefore, it is desired to develop renewable energy technologies that can produce a substitute natural gas from renewable sources. Common methods to produce methane from biological sources are anaerobic digestion and gasification. Both methods require a reliable supply of feedstock, such as food waste, woody biomass, or agricultural wastes. With the increase of renewable technologies, prices for such feedstocks are expected to rise. Therefore, additional renewable-carbon sources and the associated conversion technologies are needed to solve this energy problem. Landfills represent one possible solution, because the municipal waste that is continuously generated and the waste in existing landfill volumes are sources of carbon. Sanitary landfilling is the dominant method of solid waste disposal in the United States, accounting for about 217 million tons of waste annually (U.S. EPA, 1997). The annual production of municipal solid waste in the United States has more than doubled since 1960. In spite of increasing rates of reuse and recycling, population and economic growth will continue to render landfilling as an important and necessary component of solid waste management. The Yolo County Central Landfill accepts waste from five cities that have curb-side recycling for the residents. Yolo County Central Landfill currently does not have Material Recovery Facility (MRF) to further sort the waste delivered to the landfill.

In a bioreactor landfill, controlled quantities of liquid (leachate, groundwater, grey-water, etc.) are added to increase the moisture content of the waste. Leachate is then recirculated as necessary to maintain the moisture content of the waste at or near its moisture-holding capacity. This process significantly increases the biodegradation rate of waste and thus decreases the waste stabilization and composting time (5 to 10 years) relative to what would occur within a conventional landfill (30 years or more). If the waste decomposes in the absence of oxygen (anaerobically), it produces landfill gas (biogas). Biogas is primarily a mixture of methane, a potent greenhouse gas, carbon dioxide, and small amounts of Volatile Organic Compounds (VOC's). This by-product can be a substantial renewable-energy resource that can be recovered for electricity generation or other uses. Other benefits of a bioreactor landfill composting operation (aerobic or anaerobic) include increased landfill-waste settlement and a resulting increase in landfill capacity and life, improved opportunities for treatment of leachate liquid that may drain from fractions of the waste, possible reduction of landfill post-closure management time and activities, landfill mining, and abatement of greenhouse gases through highly efficient methane capture over a much shorter period of time than is typical of waste management through conventional landfilling. The new concept proposed in this study is to combine the methane production from a landfill bioreactor with the mining and conversion of carbon from the remaining landfill volume. Landfill space can be recovered and residual carbon-containing materials can be further converted to energy and fuels such as SNG (Synthetic or Substitute Natural Gas). Plastics and much of the lignocellulosic materials still remain, as they do not decompose readily by biochemical means. These materials can be further converted to energy and fuels by methods such as gasification. This would allow the same bioreactor cells to be reused for new municipal solid waste.

The project study entails a 12-acre module that contains a 6-acre anaerobic cell (West cell), a 3.5-acre anaerobic cell (Northeast cell), and a 2.5-acre aerobic cell at the Yolo County Central Landfill near Davis, California. The cells were highly instrumented to monitor bioreactor performance. Waste placement in the Northeast cell began on January 13, 2001 and was completed on August 3, 2001. Waste was placed in four separate lifts with an average thickness of 15 feet. In general, all waste received (residential, commercial, and industrial within the county) at the landfill was deposited in the Northeast cell with the exception of self-haul waste. Because of the difficulties handling large volumes of self-haul vehicles in the limited space of the upper lifts, self-haul waste was not placed in lifts 3 and 4. The use of daily cover soil during waste filling was minimized to aid in the overall permeability of the waste. Whenever possible, greenwaste or reusable tarps were used as alternative daily cover (ADC), and, in the event soil was placed (for example, access roads or tipping pad), the soil was removed prior to placing the next lift of waste. A total of 76,164 tons of waste was placed in the Northeast bioreactor cell and 14.5% of this was ADC greenwaste.

The aerobic bioreactor study, funded by the Greenhouse Gas Abatement program of National Energy Technology Laboratory of the U.S. Department of Defense (DOE) and in part by the California Integrated Waste Management Board (CIWMB) at the Yolo County Central Landfill was conducted to asses suppression of greenhouse methane by aeration of the landfill. This is essentially aerobic composting of landfill contents by introducing atmospheric air through the landfilled waste. An advantage of this approach is that a higher fraction of organic waste (particularly the normally significant lignin and woody lignocellulose) can be oxidized compared to the fraction of organic wastes that can be decomposed by anaerobic digestion. Thus, higher fractions of the landfilled waste can be destroyed, in turn, giving greater landfill-life extension. Disadvantages of this approach, however, include the amount of energy use required to operate the system and loss of methane energy production. The aerobic cell was operated during two aerobic-operation campaigns in 2004 and in 2006, and each aerobic operation period lasted for about six months.

Waste placement in the aerobic bioreactor cell occurred between August 8, 2001 and September 26, 2001. Waste was placed in three 10-foot lifts. Because of the limited customer dumping area of the aerobic cell, self-haul waste was excluded from this cell but all other waste (residential, commercial, and industrial within the county) were accepted. The use of daily cover soil during waste filling was also minimized to aid in the overall permeability of the waste. Whenever possible, greenwaste or tarps were used as ADC and when soil was used the soil was removed prior to placing the next lift of waste. Total of 14,111 tons of waste was placed in aerobic bioreactor cell and 15.4% of this was ADC greenwaste.

Waste placement in the West bioreactor cell occurred between March 8, 2001 and August 3, 2002. Waste was placed in four 15-foot lifts. All types of waste including the self-haul waste was placed in this cell. Whenever possible, greenwaste or tarps were used as ADC and when soil was used, the soil was removed prior to placing the next lift of waste. A total of 193,864 tons of waste was placed in the West bioreactor cell and 14.2% of this was ADC greenwaste.

In order to include the energetic conversion of the landfill digestate, it should first be quantified how much energy content is remaining after the landfill gas has been withdrawn. Other aspects are the size of the material recovered, its major composition and its contaminant level. From these data, estimates of energy potential and residue can be made. For example, based on some preliminary data collected from waste after twelve years in the landfill, it was estimated that certain size/classification fractions could contain as much as 50% lignocellulosic (wood), newspaper, cotton, carpet, rigid and film plastic materials. Hull (2005) conducted a study on a conventional landfill of similar age in New Jersey. If the recovered materials contain enough volatiles, they can be used in gasification, and the product gas can be converted to SNG. Renewable SNG is more expensive than fossil natural gas, but it could be important to at least lay the groundwork for it. If, in the future, issues such as global warming or energy security become dominant forces, SNG could be one of the solutions to use renewables on a large scale. Methanation is also one of the most effective synthesis steps in order to convert solid biomass-based fuels to a hydrocarbon fuel. Using difficult feed stocks such as waste can produce unwanted air emissions in combustion or gasification plants. The necessary cleanup before the synthesis to SNG may be an additional step to prevent unwanted elements to reach the atmosphere.

Potential magnitude and cost of SNG production were estimated as part of the project. SNG can also be produced from the landfill gas that is generated in the anaerobic bioreactors or other landfills. The question remains what to do with the remaining carbon-containing portion that takes up large landfill volumes. If this portion could be successfully extracted, this would also apply to the already existing conventional older landfills. On the other hand, if these steps are too difficult and expensive, one could consider converting any newly generated waste directly without going through the landfilling process.

Project Objectives

The goal of this project is to determine the feasibility of generating methane (and other energy) from an advanced anaerobic bioreactor which employs the concept of landfill-material recovery for energy production enabling re-use of the bioreactor cell.

> Objective 1: Determine moisture, ash, and carbon content of at least one sample already collected from an aerobic (as opposed to anaerobic) bioreactor. Determine the final number and locations of samples to be collected from the anaerobic bioreactor. The objective is that one dried size fraction contains more than 15w% carbon.
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> Objective 2: Collect at least 15 samples (5 different locations and 3 different depths) from Yolo County's bioreactor landfill cells. Categorize each sample into at least 10 different material or size groups and report those. The objective is that at least 70% of the mass is readily screened through a 1" sieve.

> Objective 3: Report proximate, ultimate elemental, and energy content (e.g., moisture, fixed carbon, volatile matter, ash, C, H, N, O, S and certain trace elements) of at least 10 samples in percent. Report composition and toxicity of ash of at least 10 minerals. The objective is that one dried size fraction contains more than 20w% carbon. Further, that this fraction contains less than 1000 ppmw Cl and 0.1 ppmw Hg.
>
> Objective 4: Report performance of sample in gasification environment such as measurement of composition of gas and solid residues. Goal is to have melting point of residual ash to be higher than 1000 C.
>
> Objective 5: Estimate the total cost of methane per cubic foot and compare it with the market price for fossil and renewable natural gas. The objective is that methane will cost less than \$15/MMBtu, and less than \$5/MMBtu accounting for landfill cost reduction.
>
> Objectives developed during the project were to:
>
> Separate the fine fraction into light and heavy fraction, so that the light fraction contains twice the amount of combustibles compared to the original fraction.

The first objective was to gain an understanding of the combustibles in the fine fractions mined from an aerobic bioreactor. The aerobic digestion produces CO_2 while anaerobic digestion produces a mixture of CH_4 and CO_2. Remaining carbon in the landfill digestate from the aerobic bioreactor could be used for energy conversion. Therefore, the goal is to obtain a large fraction of carbon. It is also of interest if the remaining combustible fraction is lower than in the anaerobic bioreactor because of the use of air.

The second objective was to collect samples from the anaerobic bioreactors in order to analyze their composition after a digestion period of about ten years. A reduced particle size of the landfill digestate could be an advantage in processing and gasifying the material. It could be readily screened and transported with automated processes, without the need for additional shredding.

Objective 3 is the main part of the study, during which the fine fraction from the anaerobic bioreactor is analyzed. Of interest is the combustible content as well as the contamination level. A high carbon content indicates a high heating value. A high ash value would negatively impact the results because the ash would be unnecessarily heated up and cooled down during gasification. Ash is also a byproduct that may be recycled or landfilled again, and therefore it is important that the hazardous contaminants do not exceed certain levels.

Objective 4 is designed to test the fine fractions in a gasification environment in order to determine which temperatures might need to be necessary for releasing most of the volatiles.

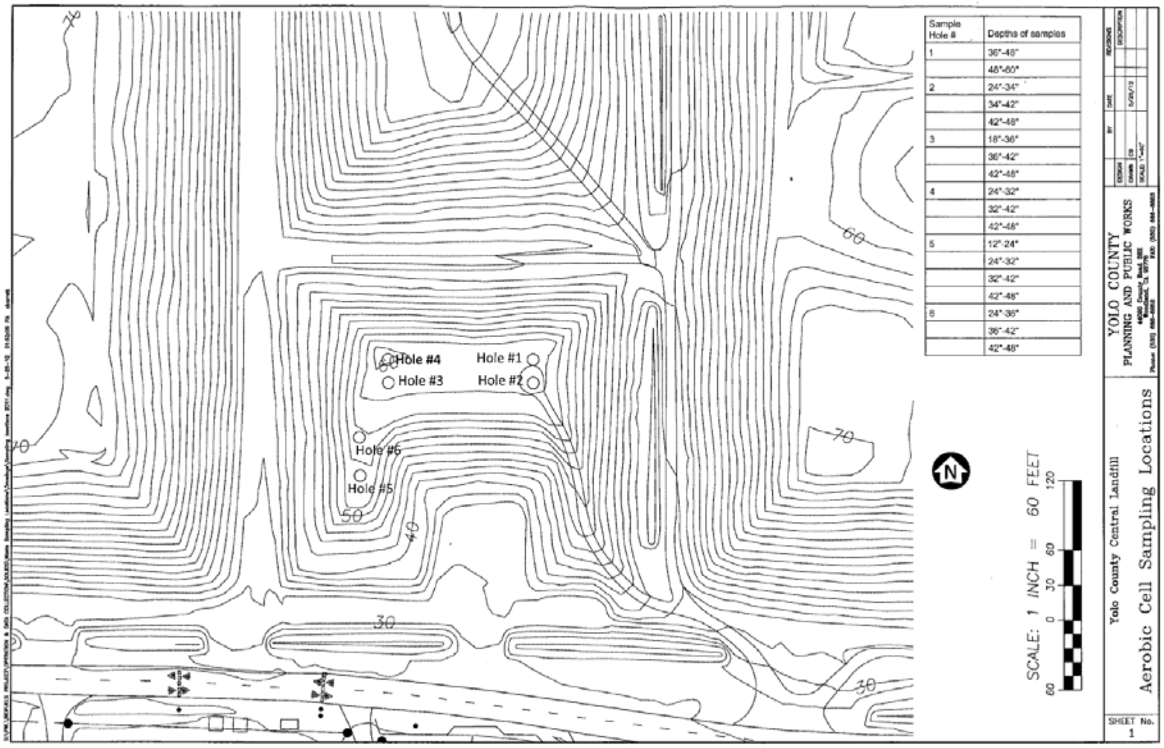
Objective 5 will estimate the cost of SNG production from both biogas and gasification of the landfill digestate. The costs will be derived from projects that employ similar technologies. With an estimated cost of SNG, it can be assessed how much SNG will cost compared to natural gas.

An objective developed during the study was to increase the combustible fraction in the fines. This will allow a better analysis of the material. For a commercial application, it would also be required to reduce the ash content to reduce handling costs and increase energy efficiency.

Project Approach

Task 1: Analyze preliminary data and design the field sampling of the bioreactor landfill cells

Figure 1 shows a site map of the aerobic bioreactor where samples had been collected previously.



Sample Hole #	Depths of samples
1	36"-48"
	48"-60"
2	24"-34"
	34"-42"
	42"-48"
3	18"-36"
	36"-42"
	42"-48"
4	24"-32"
	32"-42"
	42"-48"
5	12"-24"
	24"-32"
	32"-42"
	42"-48"
6	24"-36"
	36"-42"
	42"-48"

Figure 1: Aerobic bioreactor sampling locations. The map shows six sampling locations (holes), where samples have been removed from various depths.

Some of the samples were selected for further proximate analysis. The samples included certain size fractions from Holes #3, #4, and #6. The locations for the holes were selected such that they do not conflict with the buried pipes and instrumentation wires in the cell. The maximum depth of the excavator used limited the depth of waste excavation. It prevented a back-mixing of the waste, which could happen for deep and narrow holes created by other techniques. Analysis methods usually require small sample sizes. In order to obtain a representative sub-sample, a riffle splitter was used, as shown in Figure 2. Here, a waste sample is split into two approximately equal portions by arrays of alternate channels. This way, there is no inadvertent selectivity depending on the particle size as in other methods, where fine particles could accumulate at the bottom of the sample. By repeated riffle-splitting, the sample was reduced by approximately a factor of 16 before the sample was sent out for analysis. In the next round of sampling, samples were to be collected from the West (W) and Northeast (NE) cell anaerobic bioreactors. Five locations were identified among the two anaerobic reactor cells. The locations were selected such that they do not conflict with the buried pipes and instrumentation wires in the cell, and are away from the access road. They were also selected on top of the bioreactor cells and not on the side slopes. Excavation on the side slope would require disturbance of a larger area and could compromise the stability of the side slopes.

Figure 2: Riffle splitter for splitting a sample into a smaller sub sample. Samples were split four times in half to obtain approximately a 16th of the amount of the original sample.

Task 2: Collect samples from bioreactor and categorize samples

During the dry month of July, samples were collected from West and Northeast anaerobic bioreactor cells at designated locations. The samples were collected from each location using an excavator or a back hoe. First, the existing landfill cover soil was removed and the liner was cut open, as shown in Figure 3 and Figure 4. Samples were removed from various depths (Figure 5) and placed on a large piece of plastic liner for sampling (Figure 6). A composite sample from each distinct depth was collected and stored in a large plastic bag for further manual sorting at a later date. The excavated hole was then filled and compacted with soil and the liner was repaired and tested for gas leaks (Figure 7). Figure 8 shows the final repaired line before covering with soil.

The samples collected from the bioreactors were air-dried and prepared for screening. Once the larger fraction of waste in each bag was sorted manually, the finer fraction was sorted by a table shaker and the content classified by size. All samples were then oven-dried to determine the actual moisture content as collected from each location and depth.

Figure 3: Soil removed over the liner and area ready for excavation of cover soil below liner.

Figure 4: Excavation of cover soil below liner.

Figure 5: Excavation of waste below cover soil.

Figure 6: Excavated waste prior to collection of sample.

Figure 7: Repaired liner is scanned for methane leaks prior to placement of cover soil over liner.

Figure 8: Completely repaired liner prior to placement of cover soil and returned back to original condition.

Task 3: Prepare samples and analyze samples

From the aerobic-bioreactor samples, it was previously determined that the oven-dried samples contained only about 18wt% of combustibles. This small amount would make energy generation more costly. It also presents challenges for the precise analysis of the combustible fraction if 82wt% of the sample is taken up by inert material, especially for instruments that require a small sample size. Therefore, paths were pursued to concentrate the combustible fraction. A simple flow separation was attempted by flowing the aerobic-bioreactor sample of one size fraction across a screen with air from the bottom lifting lighter particles into a suction vent. This is shown in Figure 9. The fractions were split approximately in half by mass. Analysis showed that the light fraction (recovered from the suction vent) had a 13% higher mass fraction of combustibles than the heavy fraction (24wt% versus 11wt%). The separation technique was impacted by many variables such as downward slope of sieve, velocity of particles, mass flow of particles, air flow, and suction. Often, heavy particles were carried into the vent if they were traveling closer to the vent opening. But the separation into weight classes showed promise and was further pursued.

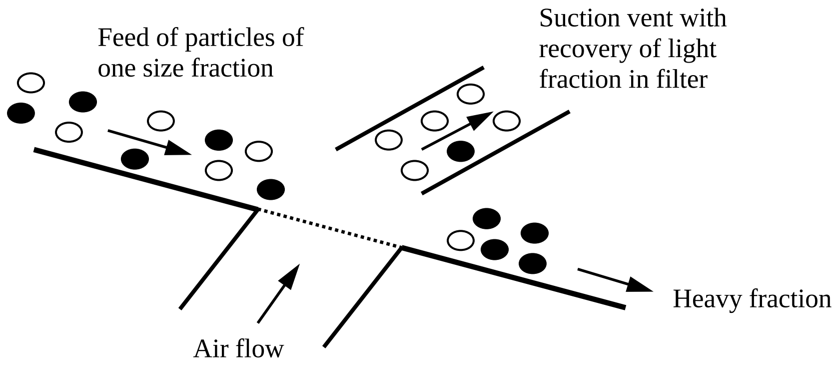


Figure 9: Separation of a size fraction using a wind sifter.

One technique to improve the separation by weight was a fluidized-bed separator (see Figure 10). This yielded a light and a heavy fraction. There was also a third fraction that was blown out of the fluidized bed and captured with a filter. The heavy and light fractions ((a) (b)
Figure 11) were analyzed for combustibles.

Figure 10: Fluidized-bed separator. Light material travels to the upper right, heavy material to the right and front.

(a) (b)

Figure 11: Light (a) and heavy (b) fraction of #8+ class after separation in fluidized-bed

The size fractions larger than a #4 sieve could not be separated in the small fluidized bed, since bridging occurred, and the fluidized bed would have to be larger for this size fraction. In order to obtain good analytical measurements and focus on the combustible fraction, a separation in a water bath was performed. Figure 12 shows the fraction that was recovered from the surface of the water bath (a), and the fraction that did not float (b).


(a) (b)

Figure 12: Light (a) and heavy fraction (b) using separation in a water bath.

This method had a major advantage in preparing the sample for analytical purposes, since the light fraction did not include as many rocks, glass, and metals, and therefore could be ground much more easily. It also gave more accurate measurements of the amount and composition of the combustible fraction as well as the ash.

In order to analyze the samples further, the light fractions from various size classes were ground to a powder. For this, a ball mill with hardened 9/16" diameter stainless steel balls was used. The samples were ground for at least 50 hours.

(a) (b)

Figure 13 shows the sample before and after grinding. Even after 50 hours, some small sticks or shells remained, as they might be too flexible for grinding. Those particles were ground by hand using mortar and pestle or in a coffee grinder.


(a) (b)

Figure 13: Light fraction of #8+ size class before (a) and after (b) grinding in ball mill

Many analysis methods require small sample volumes. Therefore, a ground and mixed sample will lead to a subsample that will better represent the overall sample composition. Figure 14 shows a picture of the ground sample of one of the light fractions.

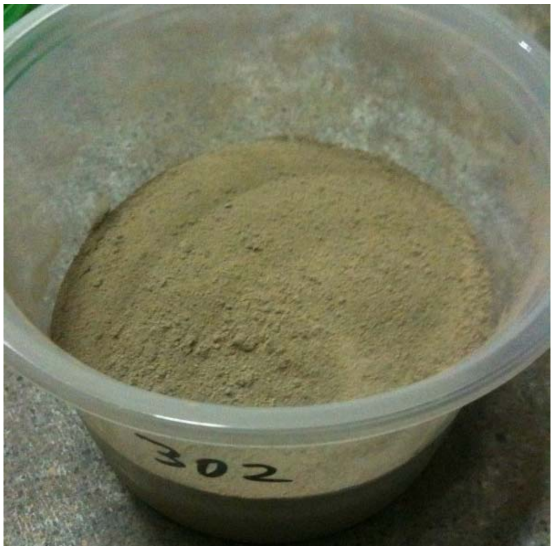


Figure 14: Ground sample of one of the light fractions prepared for further analysis.

The finely ground light fractions were analyzed with various methods. They were analyzed using proximate (ASTM methods D4442, E1755, E872) and ultimate analysis (ASTM D3176). Several elements were measured on the "as received" material because they would otherwise be lost during the generation of the ash. These include Cl (ASTM D2361), Se (SW846-7742), As (SW846-7062), and Hg. The total mercury (Hg) concentrations were determined using atomic absorption methods (LECO AMA254 Mercury Analyzer) that conform to requirements in EPA Method 7343 (EPA 1998b, Mercury in Solids and Solutions) and ASTM D-6722 2006 (Total Mercury in Coal and Combustion Residues). More information can be found in Thy (2010).

The majority of minerals were measured on the ash because it is a more common procedure. One experimental method is the relative determination of the atoms of major elements using XRF (X-Ray Fluorescence). This method is not a quantitative analysis of the entire sample, since it is only focused on selected surface measurements and considers the atoms that were selected for analysis. In order to convert the relative atom percentages into mass fractions, it was assumed that all of the measured minerals were fully oxidized. For a more quantitative analysis, especially of trace elements in smaller quantities, ICP (Inductively Charged Plasma) was used. In this method, the ash was completely dissolved in a mixture of HNO_3 and HF, and the diluted mixture subsequently injected into an Agilent 7500CE ICP-MS instrument.

Task 4: Test samples in laboratory experiment under gasification environment

To test the light and ground fractions in a gasification environment, they were analyzed in a thermo-gravimetric analyzer. The purge gas was argon which ensured the reducing environment. With this test, the weight loss of the sample was recorded as a function of temperature. The results give a measure of how easily the sample could be gasified. As instrument, a PerkinElmer Diamond TG/DTA Thermal Analyzer was used. The sample, in powder form, was placed in an open alumina crucible. It was heated at a constant heating rate of 10 C/min from temperature of ~30 C up to a final temperature 1000 C. Residues in the crucible or detection of endothermic transitions would indicate that the ash melting point is below 1000 C. A low-melting ash may cause unwanted slagging in certain types of gasifiers. To more precisely determining the ash melting point, an additional test on was performed according to ASTM D 1857. This test identifies four different characteristic temperatures during the ash fusion process. The temperatures were measured in both reducing and oxidizing atmospheres.

Task 5: Develop cost analysis of methane generation from bioreactor and methane generation from gasification

In order to determine a cost of SNG production, several approaches were used. In the first, information from the present experiments was used to update the previous cost estimates. The information included the actual amounts and composition of the manually sorted and fine fractions that were mined from the landfill. For cost of mining, processing, and re-depositing the material information from similar activities at the Yolo County Central Landfill were used.

The production rate of biogas was estimated from data generated from long-term research at the Yolo County Central Landfill. Figure 15 shows the cumulative methane generation from the anaerobic bioreactor (enhanced cell).

For the conversion of biogas and solid materials to SNG, information was gathered from other large-scale industrial processes that conduct similar processing. There are few large-scale plants that are actually gasifying waste material to make SNG. Some are converting MSW to electricity, others are converting coal to SNG. There are appreciable differences in the technologies, and they cannot simply be combined to create a waste-to-SNG plant. For example, a coal gasifier uses pulverized coal which is much easier to feed into the reactor than MSW-type material, especially under pressure. Gasifiers that operate under atmospheric pressure will need compression steps to bring the gas to higher pressure for effective synthesis and for pipeline injection. Using a compression step means that the producer gas needs to be cooled down before it is reheated to the necessary synthesis temperatures. Gas cleanup usually operates at low temperature, so a cool-down between gasifier and synthesis is required for this reason as well. The temperature of the gasifier is important for the gas composition. Lower temperatures would favor higher concentrations of CH_4 which then would not have to be produced as much from CO and H_2 in the synthesis step. Such gasifiers are more efficient, and they would also prevent ash from melting or elements from vaporizing. But they usually have higher tar content which would require an extra reformer or more expensive cleanup steps.

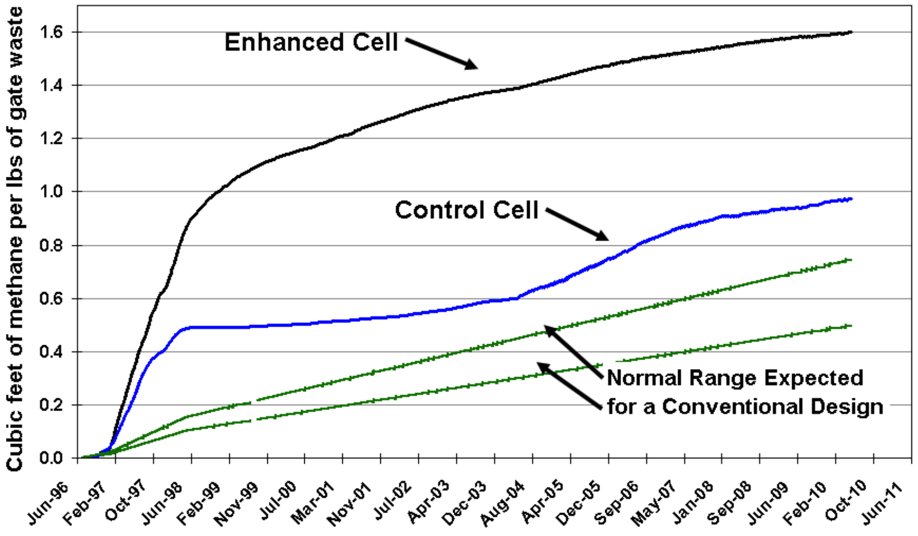


Figure 15: Cumulative methane generation in an anaerobic bioreactor (enhanced cell) versus a conventional dry landfill (control cell). The green lines are estimates for a conventional landfill based on the EPA Land GEM model.

Source: Yolo County Planning & Public Works Department

Operation with steam or oxygen presents another variable. A large amount of steam produces a high molar H_2/CO ratio, and a ratio of 3:1 is required for SNG synthesis. A lower ratio requires a water-gas shift reactor where additional steam increases the amounts of H_2 and CO_2. High-temperature gasifiers often use oxygen and then a shift reactor is required. Such a gasifier has the advantage of melting inorganics and metals and removing them from the process. But the generation of oxygen has higher costs and the higher temperatures cause a lower energy efficiency. Plasma gasifiers also fall in this category with high temperatures, but additional costs for consumption of electricity and electrodes would need to be considered. Air-blown direct-gasification processes are excluded for the current study, because it would be too costly to remove the large amounts on N_2 in order to produce SNG.

Two studies were considered to estimate capital and operating costs, a DBFZ report (DBFZ 2007) detailing a biomass-to-SNG process in a dual-fluidized-bed gasifier, and a report by Progressive Energy & CNG Services (2010) detailing a waste-to-SNG process. Both used relatively large plant sizes which is important to bring down the specific capital and operating costs. Production of SNG does not require as large plant sizes as liquid-fuel-synthesis processes to be economical. If too large, only few landfills may have the capacity to supply the required tonnage.

In the present analysis, care was taken to use the appropriate units, measurement basis, currencies, and time values of money. For example, 1 tonne (t) = 1.1 tons, 1 MMBtu = 1.055 GJ. For most calculations, dry tons and lower heating values were used. For currency exchange rates, the rate during the respective year was used, and quoted prices escalated by inflation (unless accounted for technology improvements). While these seem to be of minor importance, several 10% errors can quickly compound to an uncertainty of a factor two. Prices for capital equipment are often lower in the US than Europe, but emission standards are also higher in California. For this reason, costs of European projects were deemed as good estimates.

To obtain levelized costs of production, all prices were quoted in 2014 dollars, and computations performed on a real basis (inflation adjusted). For this, all prices were assumed to remain constant in real terms over the lifetime of the project, and the upfront capital costs were annuitized by a cost of capital of 9% above the rate of inflation of 2.4%. This nominal cost of capital of 11.4% (for a lifetime of 15 years) was deemed high enough to account for construction delays and replacement of equipment even though the project may be planned to last 20 years. The cost of capital is quoted from the point of a 100% equity holder without taxes or tax deductions. The costs also do not include any subsidies or carbon credits. Based on these assumptions, other cost scenarios can be derived for particular circumstances.

Costs were taken, whenever possible, from actually working projects. The DBFZ report (DBFZ 2007), was based on a 1-MW demonstration plant, and it accounts for numerous process steps, consumables, and waste streams. It also includes scaled-up costs for a plant size up to 500 MWLHV. Figure 16 shows a schematic of all the individual process steps included in the DBFZ report.

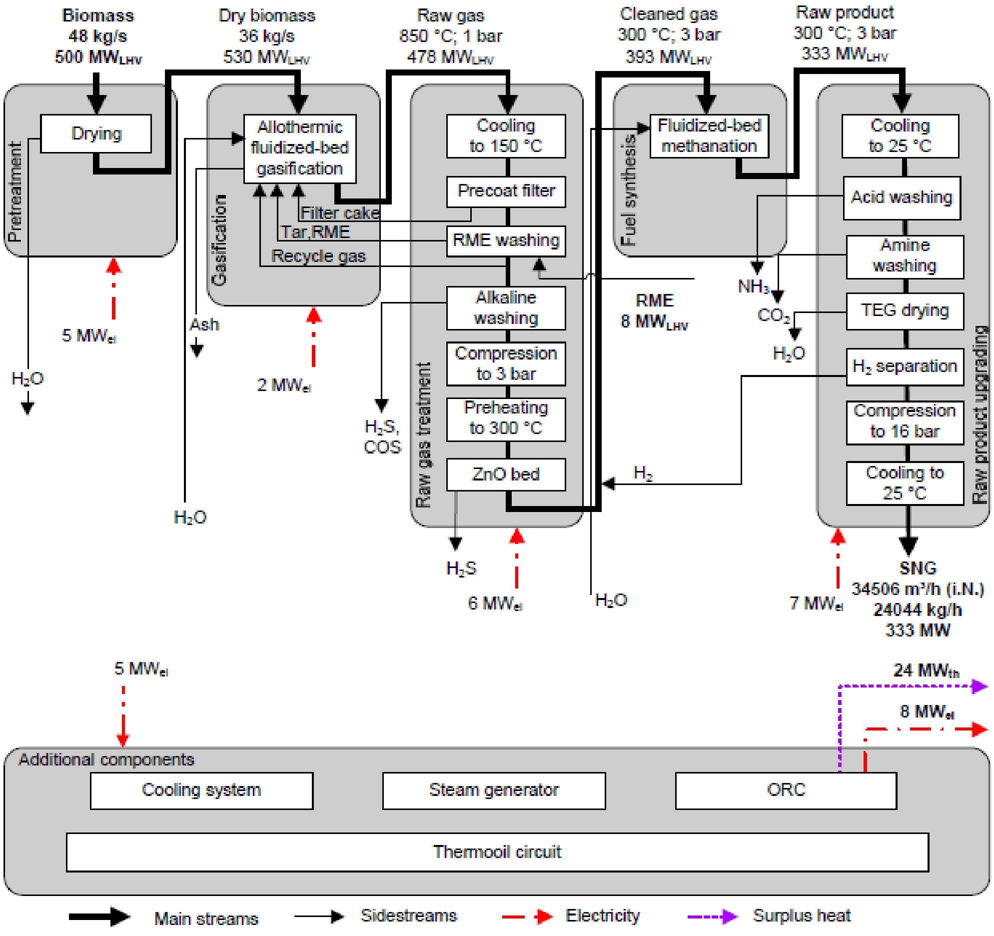


Figure 16: Flow schematic of 500 MW Bio-SNG process

Source: Position of Bio-SNG compared to other biofuel options from lignocellulosic feedstocks (DBFZ, 2009)

Project Outcomes

Objective 1: Determine moisture, ash, and carbon content of at least one sample already collected from an aerobic (as opposed to anaerobic) bioreactor. Determine the final number and locations of samples to be collected from the anaerobic bioreactor. The objective is that one dried size fraction contains more than 15w% carbon.

Figure 17 shows the weights of the various mass fractions that were recovered from the aerobic bioreactor. The smaller fractions that were not easily identified (fines) were classified by size. On average, the total moisture content was 39.5w% (25w% was removed during air drying and 14.5w% during oven-drying). The remaining 60.5w% was the weight of the oven-dried samples (27.8w% manually sorted and 32.7w% screened through sieves). All weight fractions are shown on a wet basis, which is based on the total weight of the original (wet) sample. Figure 18 shows the mass distribution of the samples on a oven-dried basis. On average, 45w% of the dry weight was manually sorted, and 55w% was screened through sieves.

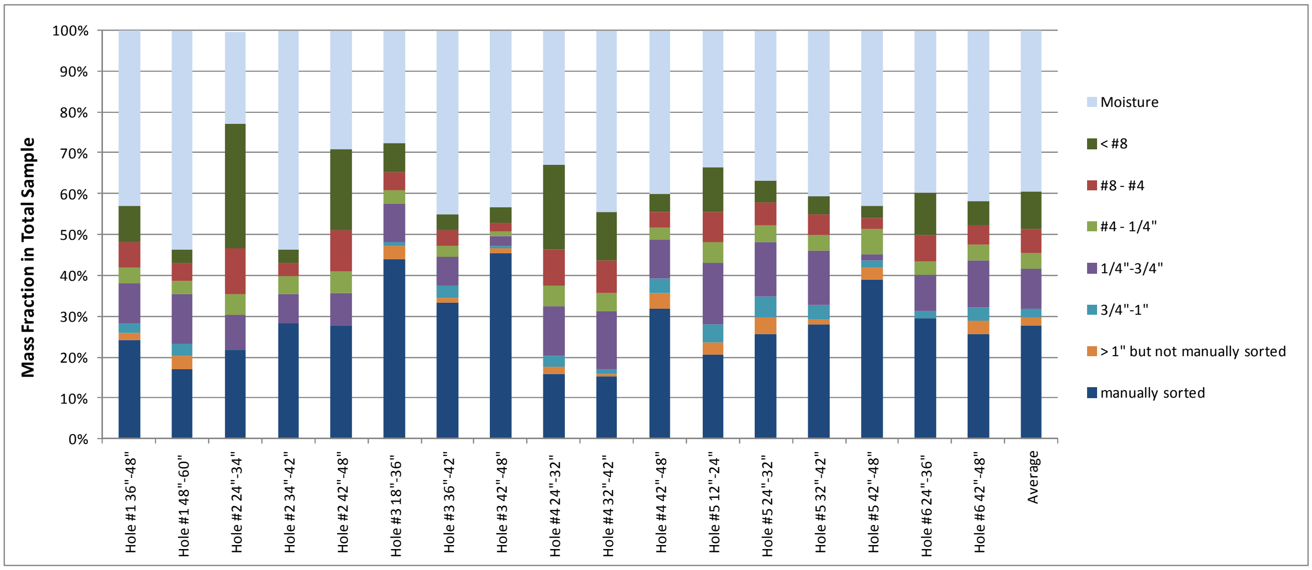


Figure 17: Mass distribution of samples from the aerobic bioreactor. The weights are shown on a total sample basis (wet basis).

Figure 19 shows the size fractions that were further analyzed for moisture, ash, and combustibles. The proximate analysis was performed on triplicates, and the standard deviation was approximately 8%. The results show that in the oven-dried samples, there was very little moisture left (2.6w%). Most of the samples had a high ash content (80.2w%) and a smaller combustible fraction (17.2w%). Since the combustible fraction is expected to contain a high amount of oxygen (biomass origin), the estimated amount of carbon is 10w%. This is below the objective of 15w% and would make an energetic usage of the material more difficult and expensive.

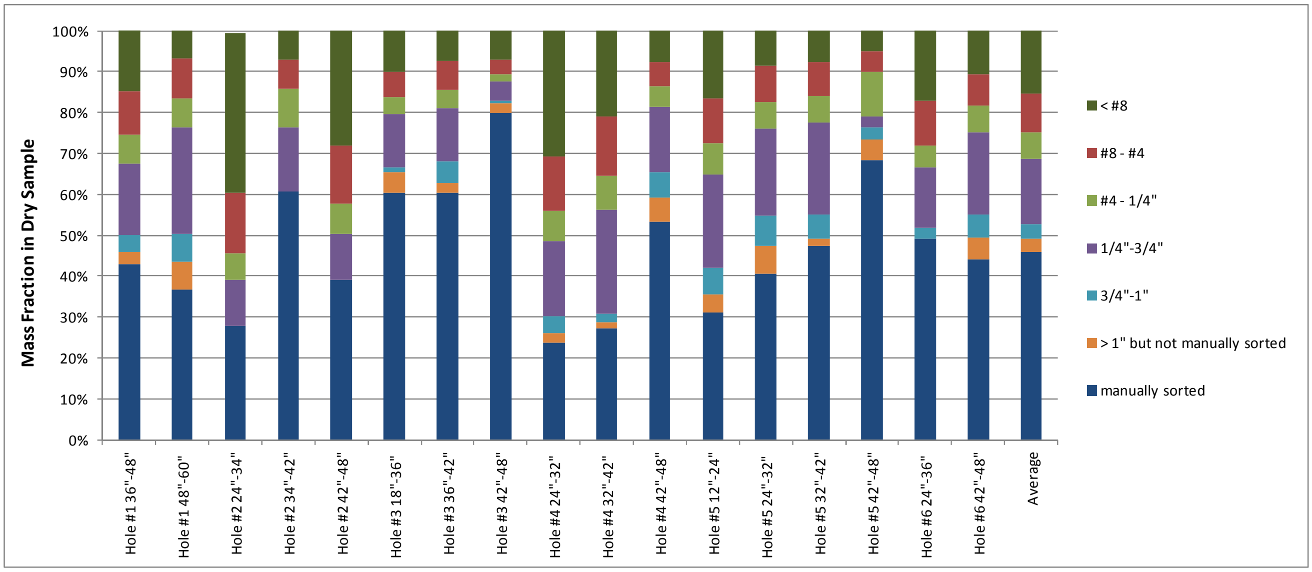


Figure 18: Mass distribution of oven-dried samples from the aerobic bioreactor. The weights are shown on an oven-dried basis.

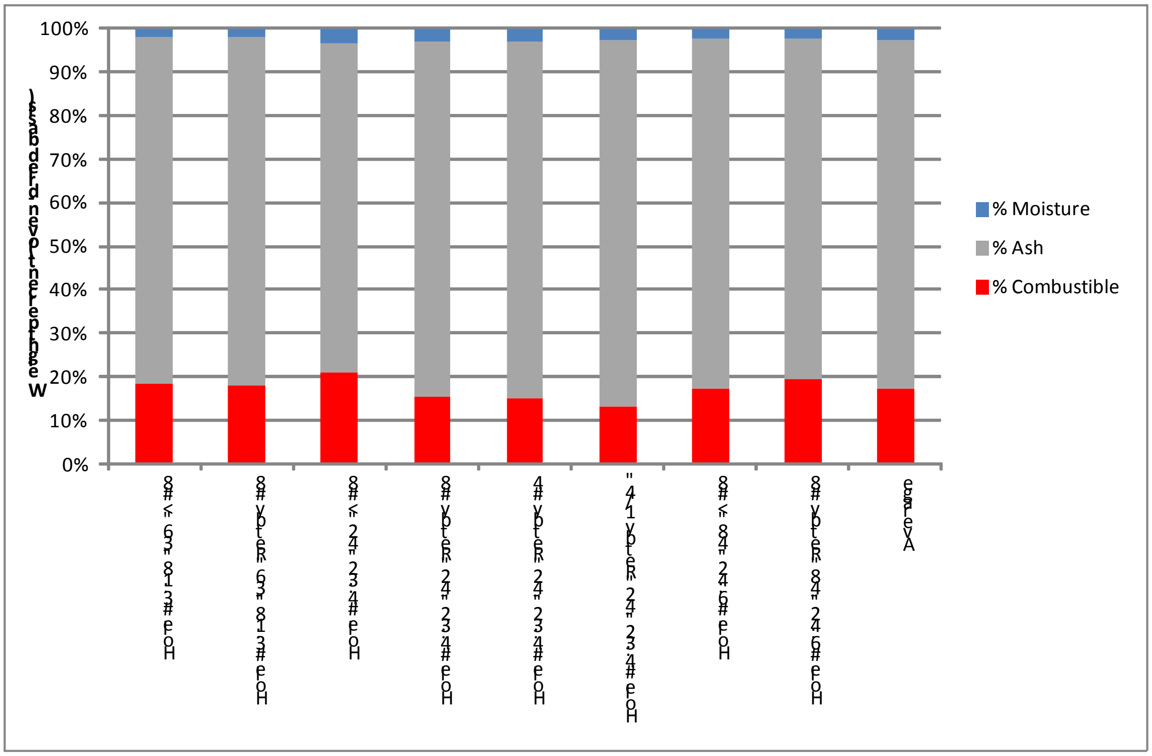


Figure 19: Combustible fraction in oven-dried samples from the aerobic bioreactor. The weights are shown on an oven-dried basis.

For the anaerobic bioreactor cells, the final locations of the sampling holes were determined. Figure 20 shows the three sampling locations for the West cell, and Figure 21 shows the two sampling locations for the Northeast cell.

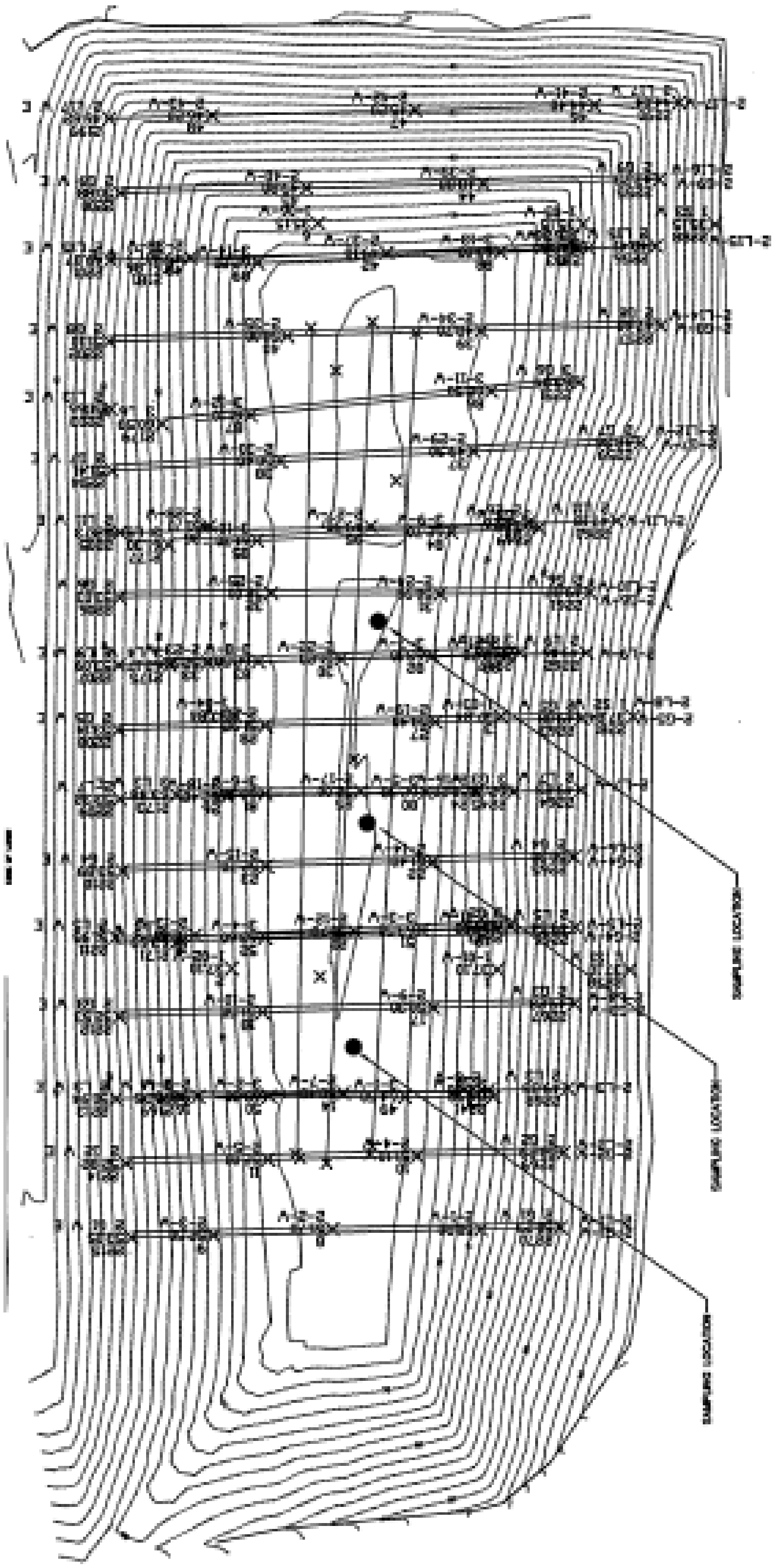


Figure 20: Selected sampling locations on the West cell anaerobic bioreactor.

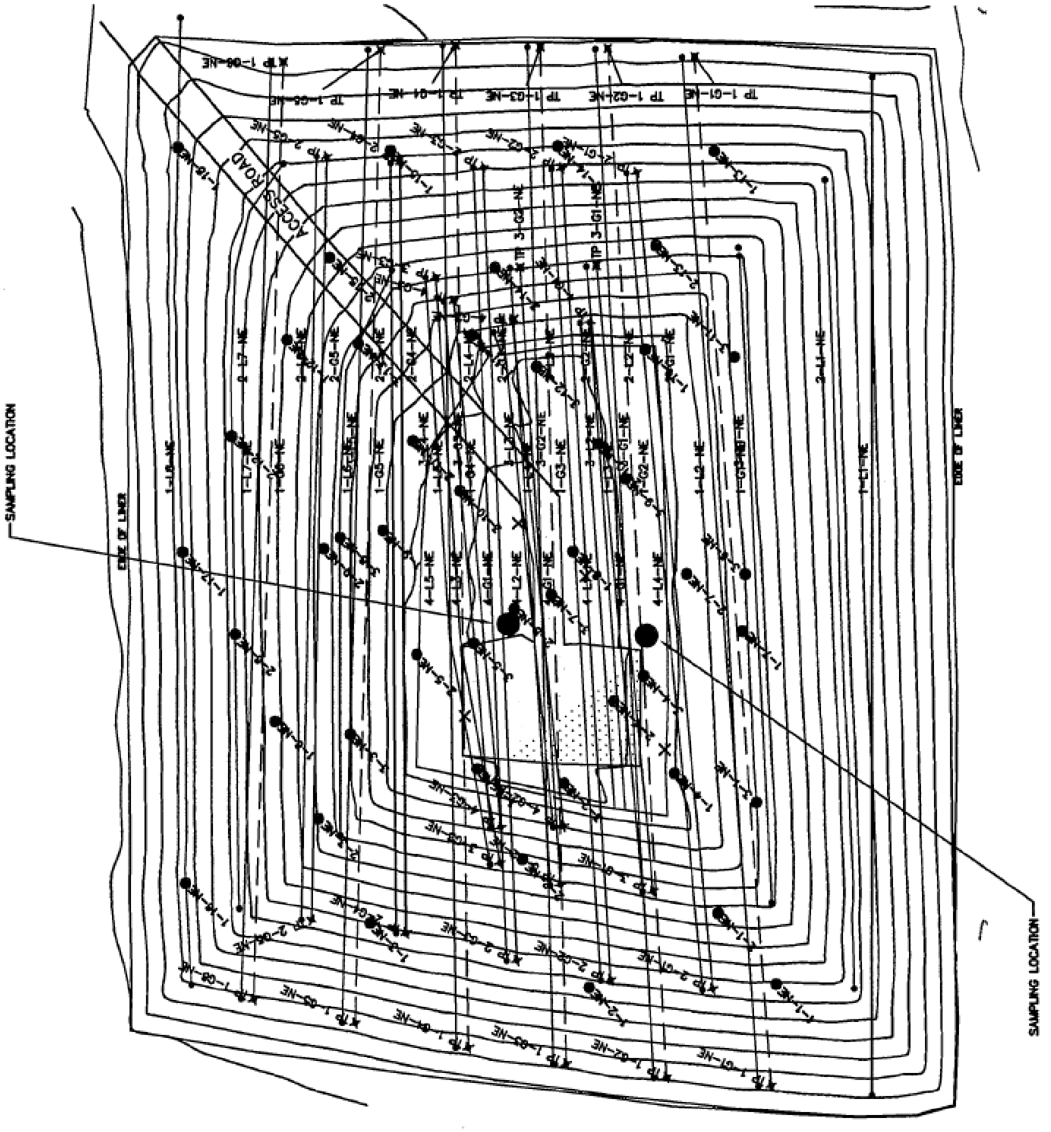


Figure 21: Selected sampling locations on the Northeast cell anaerobic bioreactor.

Objective 2: Collect at least 15 samples (5 different locations and 3 different depths) from Yolo County's bioreactor landfill cells. Categorize each sample into at least 10 different material or size groups and report those. The objective is that at least 70% of the mass is readily screened through a 1" sieve.

The samples from the anaerobic bioreactors were collected and categorized by depth. The West cell yielded 13 samples from three hole locations. The Northeast cell yielded 7 samples from two hole locations. These samples (20 total) were categorized into 8 size classes. The results are shown in Figure 22 and Figure 23. The mass distribution is reported on a wet basis (total mined sample) and includes the moisture that was removed during air- and oven-drying. Figure 24 shows the waste categories after sorting. It shows the averages for the aerobic cell, the anaerobic West cell, and the anaerobic Northeast cell. A noteworthy difference lies in the paper and cardboard fraction which was lower in the aerobic than in any of the anaerobic bioreactors. Figure 25 shows the waste categories on a relative energy basis. The fine fractions in the anaerobic cells were 46w% which is below the objective of 70w%.

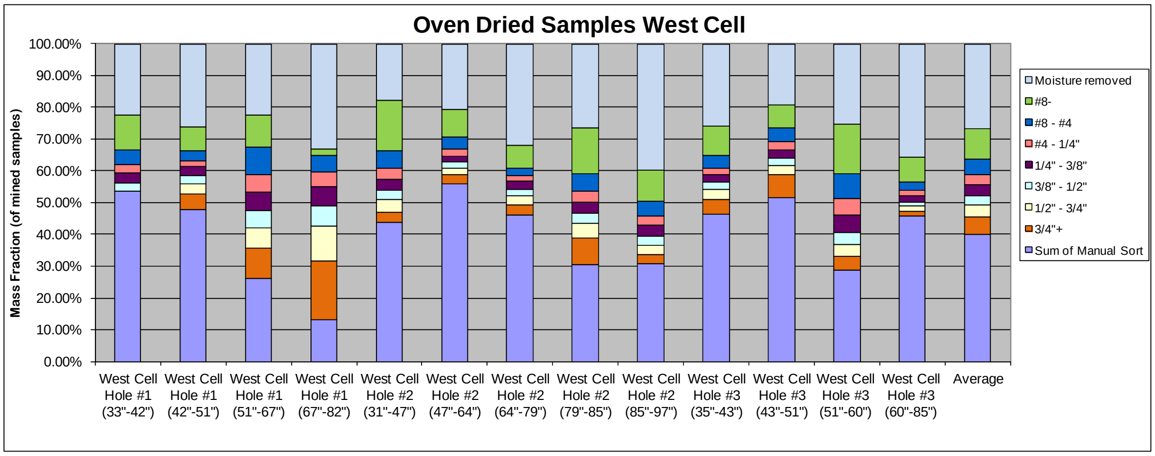


Figure 22: Size fractions recovered from samples taken from the anaerobic bioreactor (West cell)

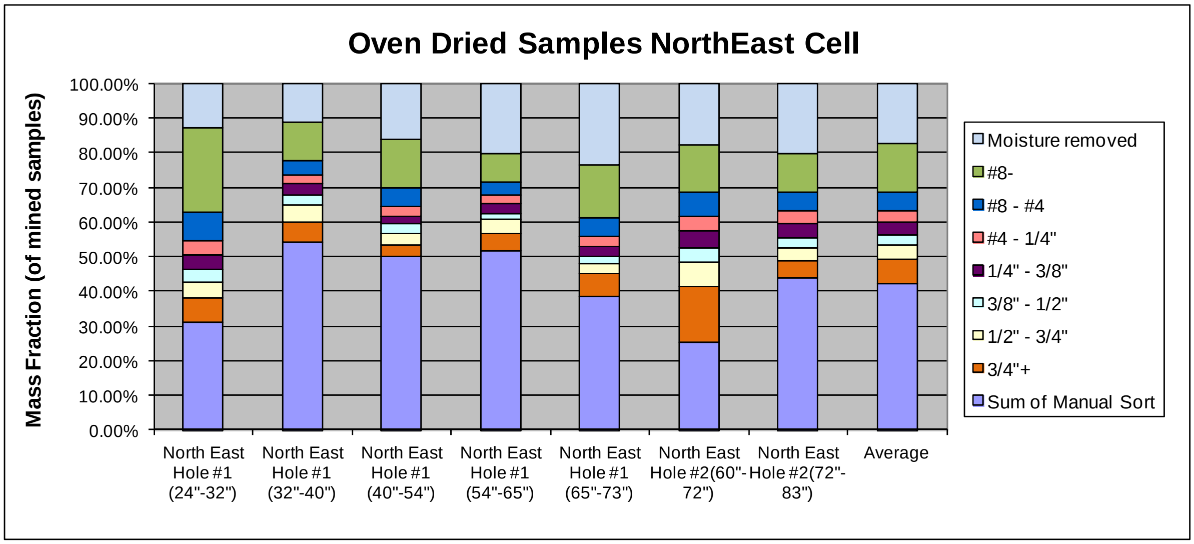


Figure 23: Size fractions recovered from samples taken from the anaerobic bioreactor (Northeast cell)

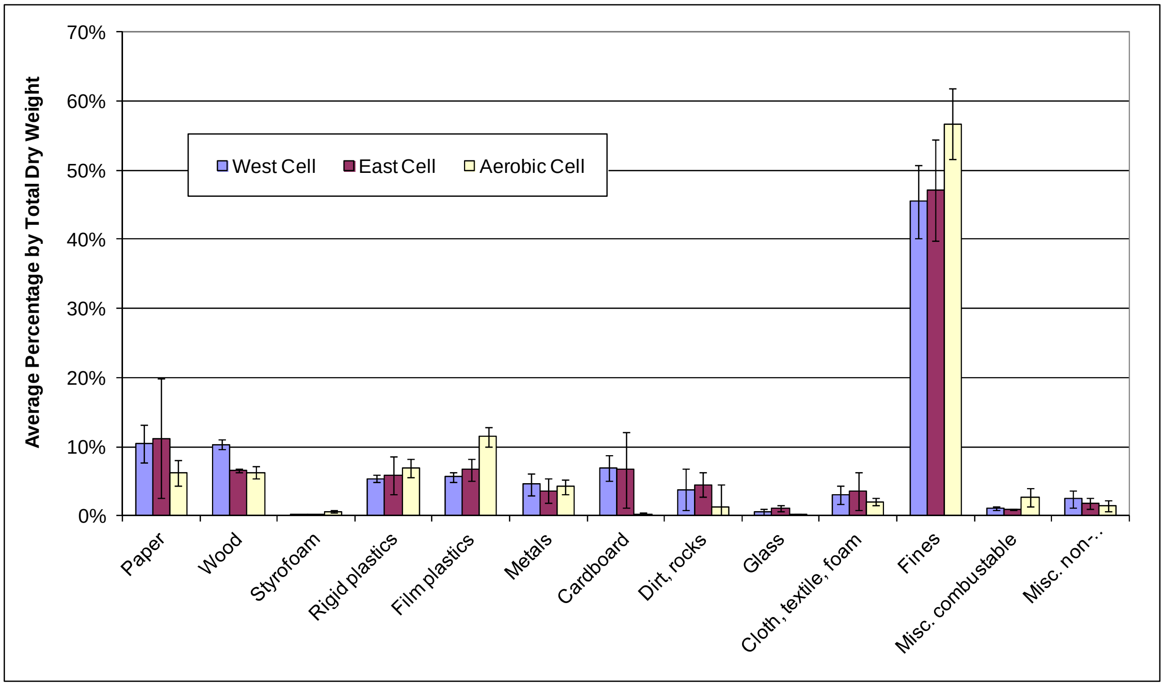


Figure 24: Waste categories by relative dry mass in aerobic and anaerobic bioreactors

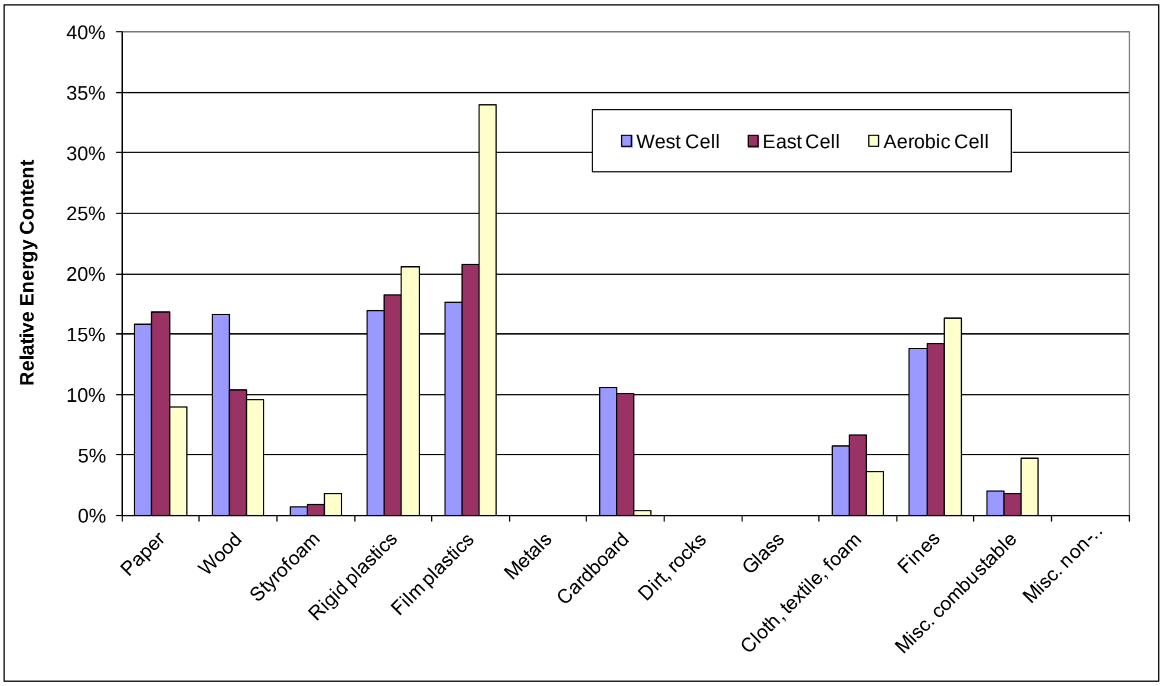


Figure 25: Waste categories by energy content in aerobic and anaerobic bioreactors

Objective 3: Report proximate, ultimate elemental, and energy content (e.g., moisture, fixed carbon, volatile matter, ash, C, H, N, O, S and certain trace elements) of at least 10 samples in percent. Report composition and toxicity of ash of at least 10 minerals. The objective is that one dried size fraction contains more than 20w% carbon. Further, that this fraction contains less than 1000 ppmw Cl and 0.1 ppmw Hg.

Several samples were analyzed for combustibles after they were classified by size and oven-dried. Figure 26 shows the results of five samples. The combustible fraction is between 12w% and 35w%. The sample from the Northeast cell shows the highest combustible fraction for both #8- and #8+ fractions.

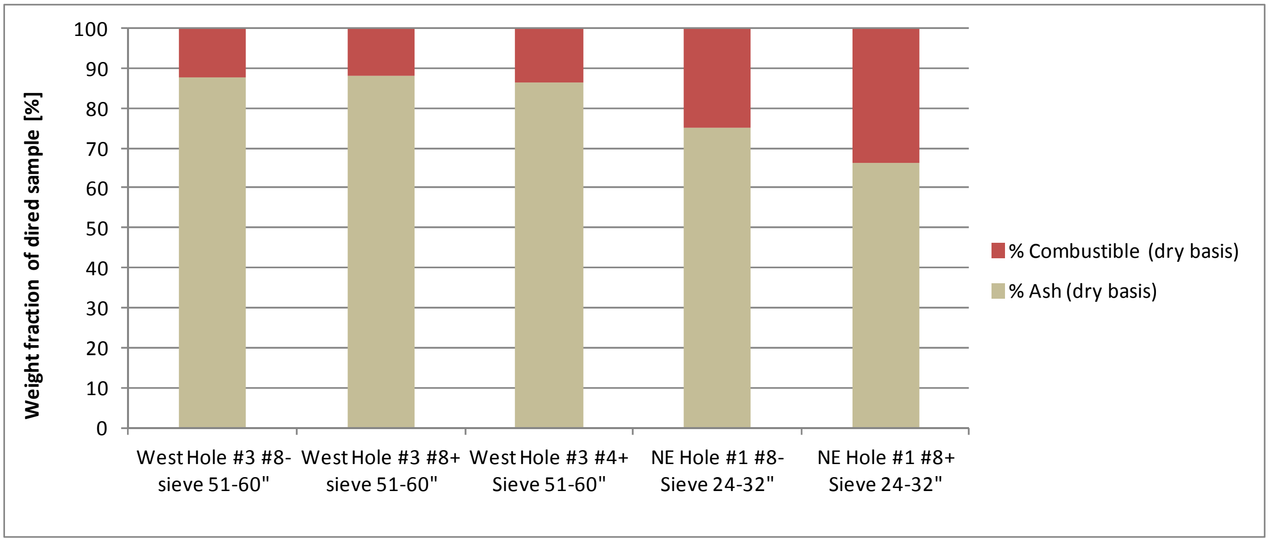


Figure 26: Combustible and ash fractions of various samples of the anaerobic cells

Table 1 shows the overview of two samples separated by weight. From the #8+ class, a small amount of the light fraction was separated (30.5g), and it contained 85w% combustibles. From the #8- class, the fractions separated were more similar in size (light: 116g, heavy: 148g), but their combustible fractions were also closer together (35.9w% in light fraction, 20w% in heavy fraction). This indicates that for the same particle size, the combustibles are lighter than the non-combustibles, and this could be used to increase the combustibles content of the fines to be used in the gasification process.

	Wet				Dry		
Sample Name	Solids [%]	Ash [%]	Moisture [%]	Weight [g]	Combustibles [%]	Ash [%]	Weight [g]
#8+ Sieve NE Hole 1 24-32 Fines				11.5			
#8+ Sieve NE Hole 1 24-32 Light	97.0	14.1	3.0	30.5	**85.4**	14.6	29.6
#8+ Sieve NE Hole 1 24-32 Heavy	98.9	80.5	1.1	285.5	**18.6**	81.4	282.4
#8+ Sieve NE Hole 1 24-32 Non-separated					**33.9**	66.1	
#8- Sieve NE Hole 1 24-32 Fines				19.0			
#8- Sieve NE Hole 1 24-32 Light	83.4	53.4	16.6	116.0	**35.9**	64.1	96.7
#8- Sieve NE Hole 1 24-32 Heavy	88.6	70.6	11.4	148.0	**20.3**	79.7	131.1
#8- Sieve NE Hole 1 24-32 Non-separated					**25.0**	75.0	

Table 1: Light and heavy fractions after fluidized-bed separation

Several other samples were subsequently analyzed for combustibles. Figure 27 shows the results for 18 samples from five locations. The combustible fraction was on average 16w% on a dry basis. No statistically significant trend was found in terms of sampling depth or size class.

Further samples were separated into light and heavy fraction in a fluidized bed or with water. This allowed to focus on the light fraction which, as shown above, contained a higher amount of combustibles. This would make energetic usage more effective in a practical application, and it also helped the chemical analysis, since the sample contained less rocks and glass. Figure 28 shows the amount of combustibles in the light fractions. On average, separation by water was the more reliable method to increase the combustibles content of the sample.

The ultimate analysis of the ground-up light fractions determined the composition of the elements C, H, N, S, and O (Figure 29). On average, it was found that the samples contained about 55% carbon and 33% oxygen. This indicates a biomass-type of material. Plastics are mostly pure hydrocarbons, and would not contain any oxygen. On the right side in Figure 29 is shown what the ultimate analysis of typical wood chips, coal, and plastics would look like. The measured averages of the samples are closer to wood than to coal. The analysis also indicated some nitrogen and sulfur in the analysis. Sulfur is a source of SO_2 and catalyst poisoning and needs to be removed for most conversion processes.

From the proximate analysis (16w% combustibles) and ultimate analysis (55w% C), it can be calculated that the carbon content of the fines is 8.8w%. This does not meet the objective of 20w%. Considering a separation by weight, where the combustibles content in the light fraction can rise up to 70w%, the carbon content would rise to 38.5w%. This, however, means that only a small portion of the fines is utilized and the remainder will need to be landfilled again.

A biocarbon analysis was conducted on two size classes for which several individual samples were mixed together (proportionally to their sample size). Both size fractions showed that most of the carbon was biogenic carbon and not fossil carbon, indicating wood sources. The #8+ size fraction had 85% modern (biogenic) carbon, and the #4+ size fraction had 95% modern carbon (Figure 30). This confirms that the fine fractions in the digested landfill waste are mostly renewable materials.

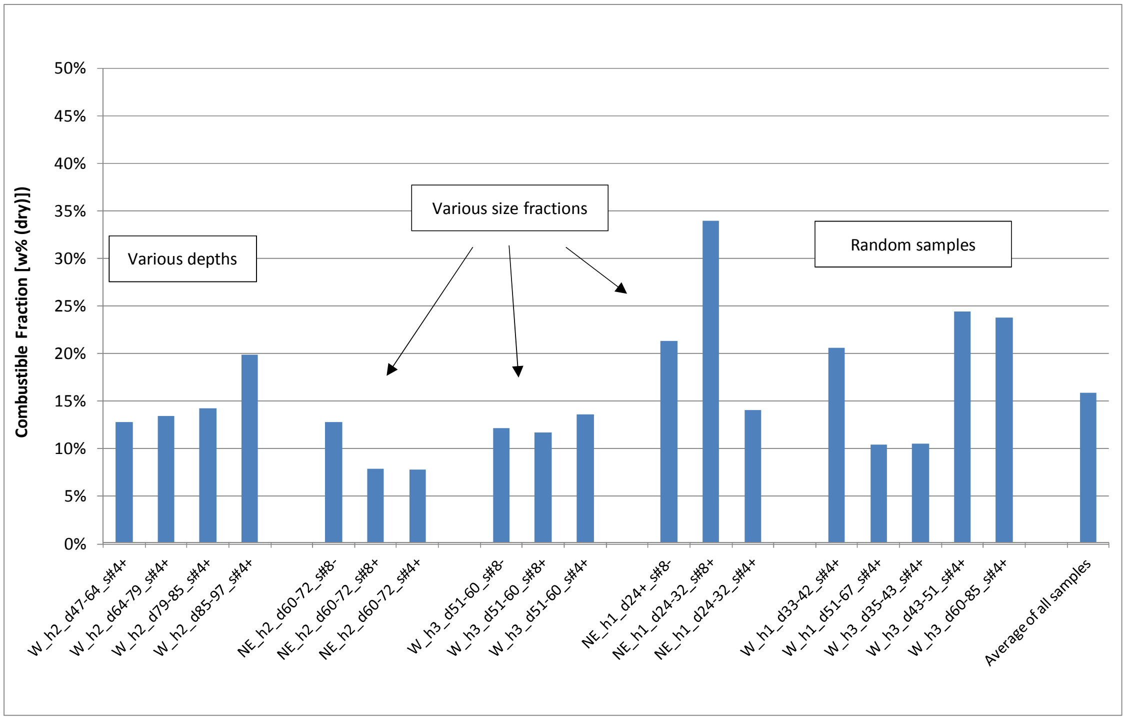


Figure 27: Analysis of the combustible fraction for various samples from the anaerobic bioreactors

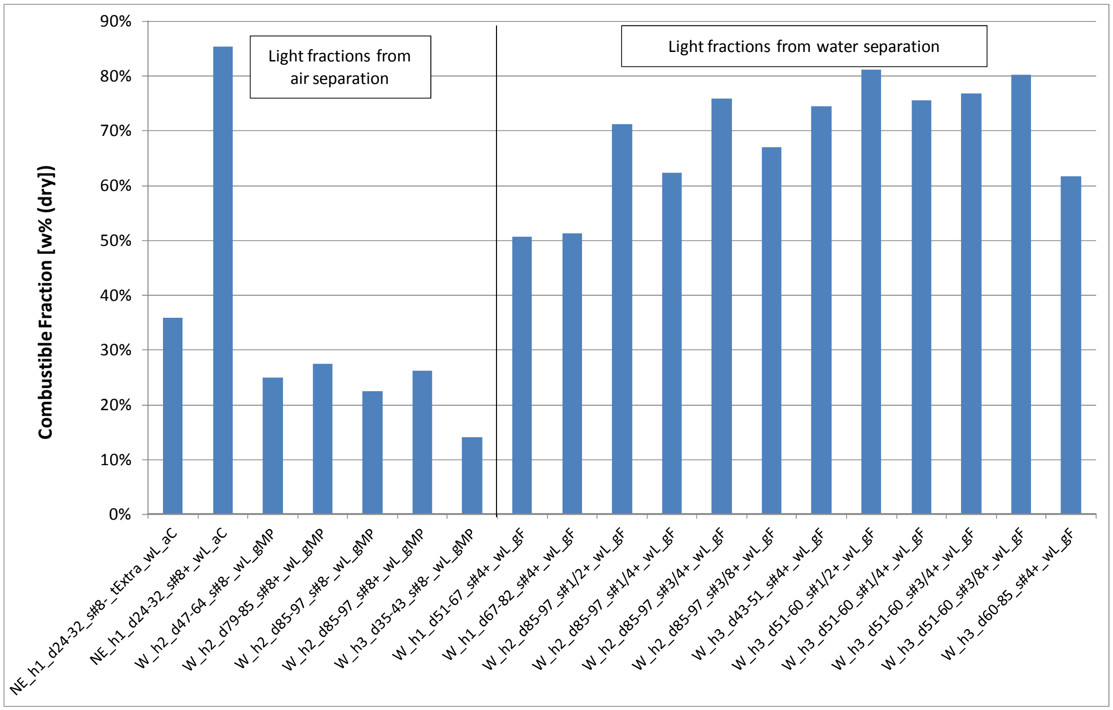


Figure 28: Analysis of combustibles in the light fractions that were analyzed

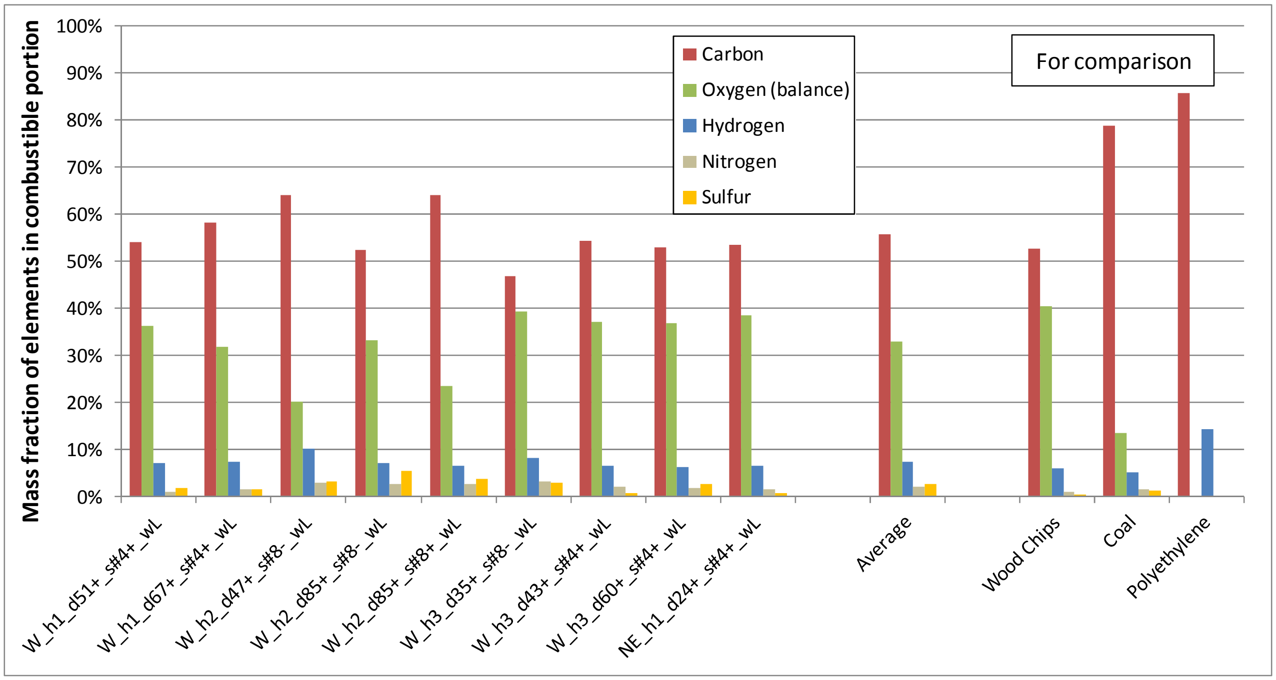
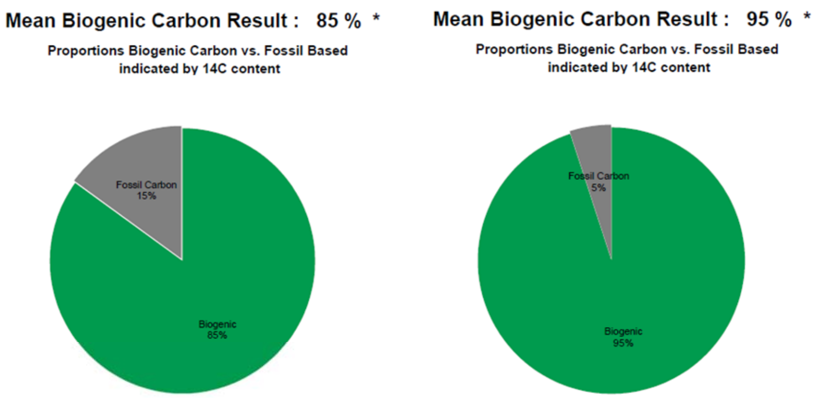


Figure 29: Ultimate analysis of light fractions of various size fractions



a) **#8+ size fractions from 3 samples**

b) **#4+ size fractions from 5 samples**

Figure 30: Biocarbon analysis of two size classes (#8+ and #4+).

Ash generated from the determination of the combustibles was analyzed for major minerals. Figure 31 shows the percentages of eight measured elements. The results show that the major elements are Si and Fe. The composition also gives a guide in regards to the ash melting point. For example, Si and K have low melting points, especially if in combination through the formation of alkali silicates (Wang, 2008). This can cause problems in certain types of gasifiers.

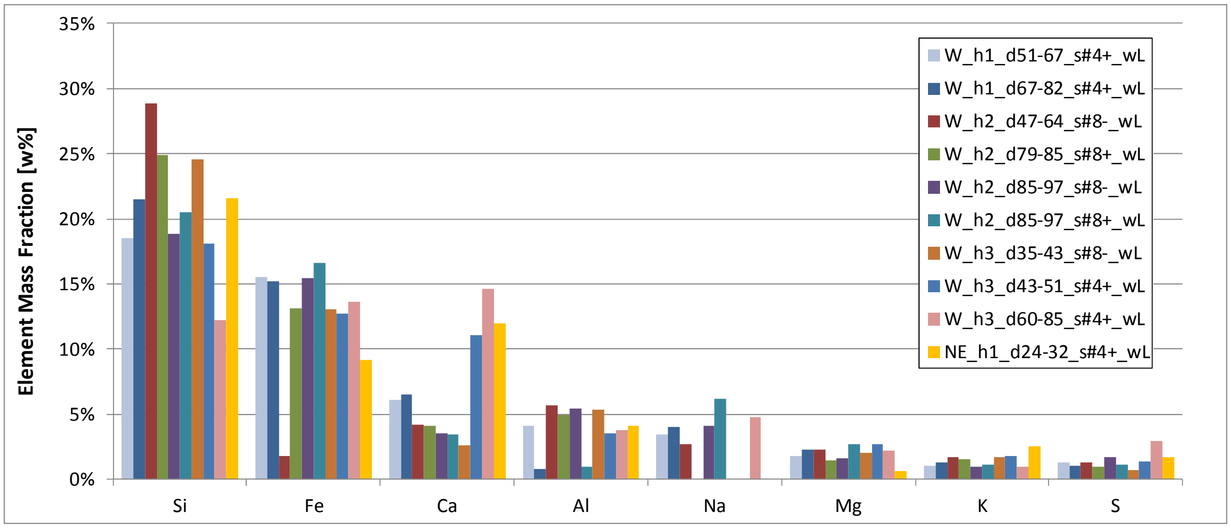


Figure 31: XRF analysis of major minerals in the ash generated from the light fractions of several samples.

Figure 32 shows the results of the measured trace elements by ICP in ppmw. The analysis was performed on the ash generated from various light fractions of the fines. Chromium is approximately 1000 ppmw in the ash. Since stainless-steel balls were used in the grinding of the materials before ashing them, there is a possibility that some of the chromium was introduced during the grinding process. This could be verified in the future by grinding one sample with a different material of the grinding media. (A sample was attempted to be ground using alumina balls, but too many rocks were still left after grinding for several days, and therefore a different milling process or ball material may be necessary.) Some of the elements cannot be reliably measured in the ash because they are volatile and would evaporate during the ashing process. These elements were analyzed separately on the original material (as-received basis). Figure 33 shows the results for Cl, As, Se, and Hg in six different light fractions. Chlorine is an important element to watch since it can form PCBs (Polychlorinated Bi-phenyls, e.g. dioxins). In gasification, chlorine can be bound in calcium chloride which is harmless (used in food additives). Chlorine and mercury are close to, but above, the target objectives and therefore will need to be well monitored and controlled in a practical energy conversion process.

The resulting waste categories and trace components are very similar to those found in excavated materials from a conventional landfill of similar age in New Jersey (Hull, 2005). One difference appeared in the chromium levels, because that study reported values for hexavalent chromium only.

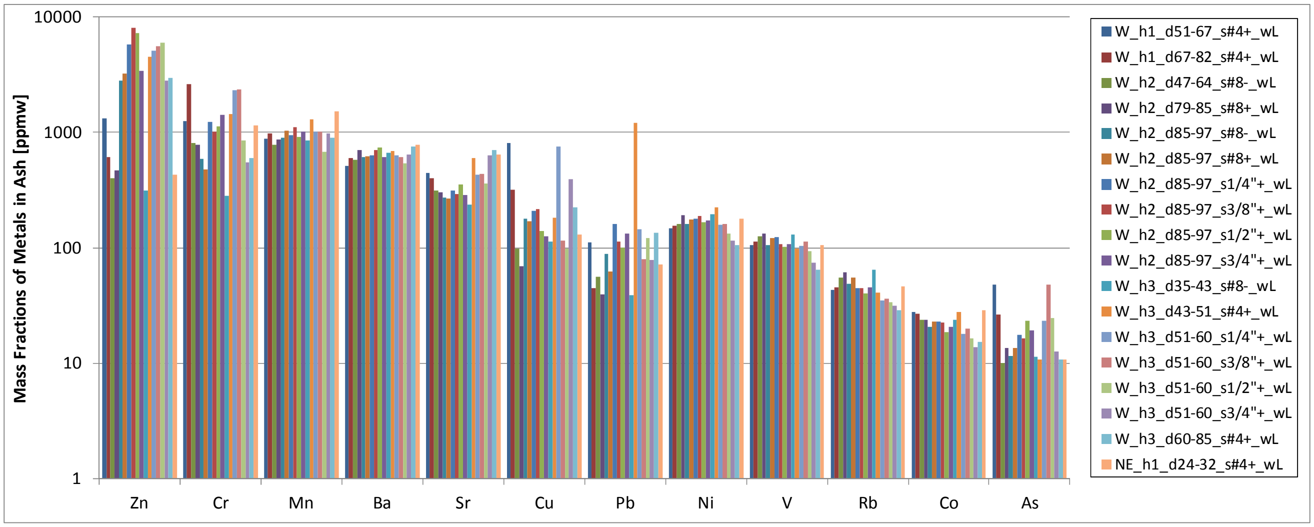


Figure 32: ICP analysis of trace minerals in the ash generated from the light fraction of several samples.

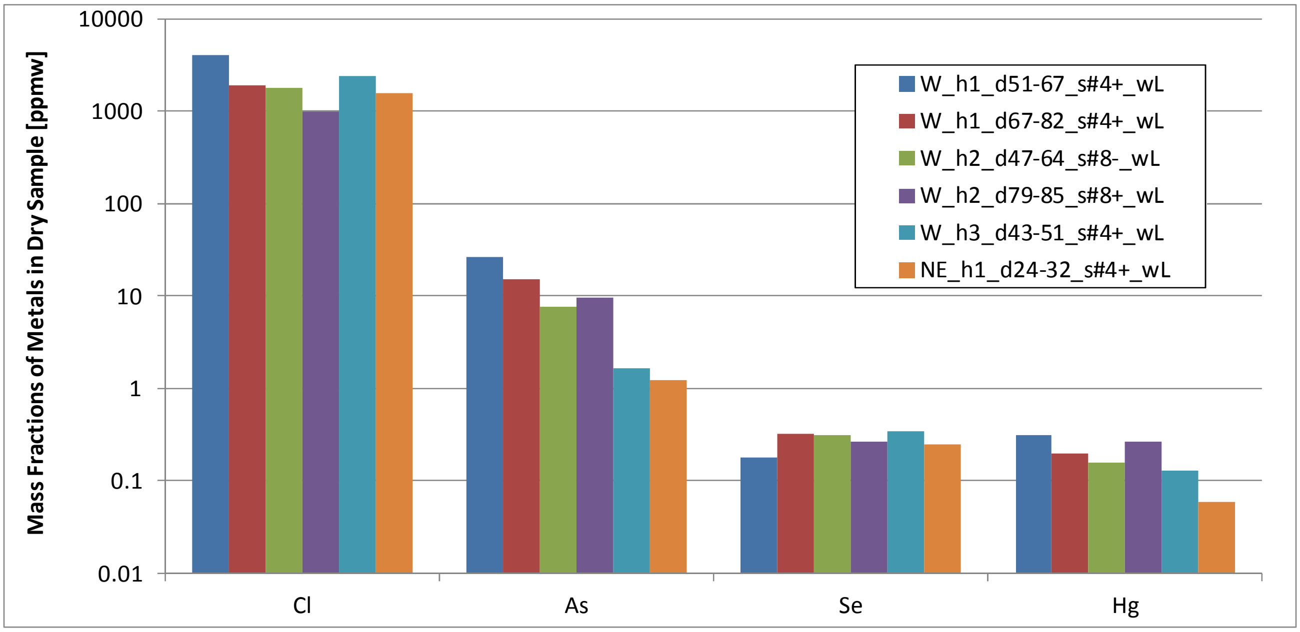


Figure 33: Analysis of chlorine and trace minerals in the light fraction of several samples

The energy content of the mined material was estimated based on both the manually sorted fraction and the fine fractions. Of the manually sorted fraction, it was assumed that wood, plastics, paper, cardboard, and textiles would be used for the energetic conversion, while metals, glass, and inorganic materials would be recycled. Of the wood, paper, and cardboard fraction, a small amount is considered as reject (4%), which accounts for contamination. Of the plastics fraction, it is assumed that PVC and similar material is removed. While it was not measured, the fraction of PVC seemed to be very small, and 88% of the plastics are considered for the energetic conversion. If the recycling of plastics yield a higher value than the conversion to SNG, this may also be considered as an alternative path. Textiles include fabrics and carpets, and some of those may not be optimal for gasification. Therefore, it was assumed that only two-thirds of the textiles would be used. For the fine fraction, it was assumed that it could be successfully separated into a light fraction that has a higher energy content. The overall energy content of the fine fraction was 16w% and it was assumed that 67w% of these combustibles end up in the light fine fraction, while the rest would be lost in the heavy fraction. This is equivalent with a light fraction of 15w% containing 70w% combustibles which was observed (see Figure 28) for the separations in water (16% x 67% = 70% x 15%). Among the non-combustibles in the fine fraction, 95w% of these were removed with the heavy fraction. An improvement in the separation technique would be desired to harness a larger portion of the combustibles which would slightly increase the overall energy content in the mined landfill digestate. Table 2 shows a summary of the energy content. For wood, paper, plastics, and textiles, the lower heating values were taken from the literature (EIA 2007, World Bank 1999). For the combustibles in the fine fraction, the energy value was computed from the ultimate analysis, which was slightly higher than for wood. Adding up the energy content for all fractions yields a value of 9 MJ per kg of dry landfill digestate. The material that would actually be fed to the gasifier is 45% of the mass (38% Manual Sort + 7% Fine Fraction = 45%) and has an energy content of 20 MJ/kg.

	Fraction in Manual Sort/ Fine Fraction	Portion of Manual Sort / Fine Fraction in total	Usable amount	Fraction of total used for energy	Energy content of fraction	Energy content per mined kg
	w%	w%	w%	w%	MJ/kg	MJ/kg total (dry)
Wood	16%	54%	96%	8.3%	17	1.41
Paper	20%	54%	96%	10.4%	16	1.66
Rigid and film plastics	22%	54%	88%	10.5%	33	3.45
Cardboard	13%	54%	96%	6.7%	16	1.08
Textiles	6%	54%	66%	2.1%	20	0.43
Metals, glass, rocks	23%	54%		0.0%	0	0.00
Total for Manual Sort		54%		38.0%	21	8.02
Combustibles in Fine Fraction	16%	46%	67%	4.9%	20	0.98
Non-combustibles in Fine Fraction	84%	46%	5%	2.1%	0	0.00
Total for Fine Fraction		46%		7.0%	14	0.98
Total		100%		45.0%	20	9.01

Table 2: Energy content of mined landfill waste considered for SNG production

Objective 4: Report performance of sample in gasification environment such as measurement of composition of gas and solid residues. Goal is to have melting point of residual ash to be higher than 1000 C.

Six of the samples were analyzed in a Thermo-Gravimetric Analyzer (TGA). The samples were produced from screening and weight separation, since the light fractions had a higher combustibles content and could be readily ground into a fine powder. The thermo-gravimetric analysis was performed under argon atmosphere and with a heating rate of 10 C/min. The weight of the samples was recorded over time. Figure 34 shows the results. Here, the rate of weight change is plotted as a function of temperature. The results are consistent with the initial devolatilization of cellulosic and hemicellulosic fractions in the material and show that the highest rates of devolatilization appears below 400 C, and most of the volatiles have formed below 500 C. These results indicate that enough volatiles are available in these samples for gasification and that the sample is not just fixed carbon.

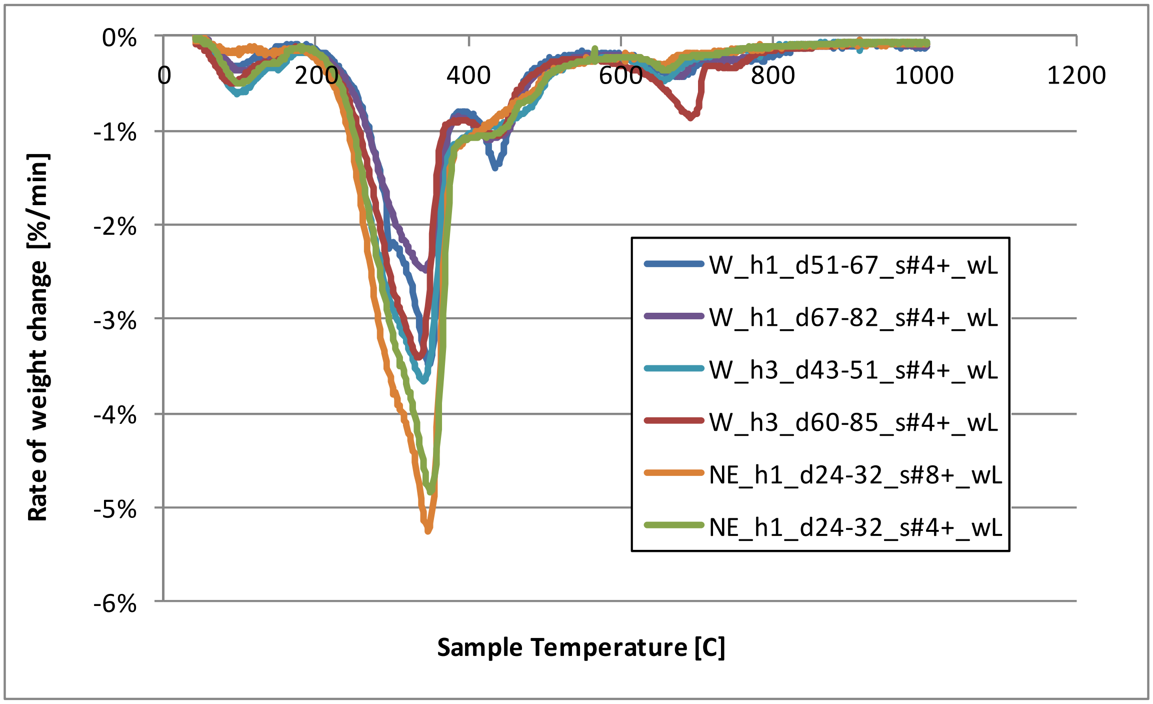


Figure 34: TGA results for six samples mined from the anaerobic bioreactors. The weight-loss rate is shown as a function of temperature. The heating rate was 10 C/min and the atmosphere was argon.

Figure 35 shows the average TGA result of the six samples from the anaerobic bioreactor and also a comparison with cellulose. The rate of weight change shows that cellulose devolatilizes in a very narrow temperature range around 360 C. The landfill samples devolatilize over a wider temperature range, since they contain a mixture of various components. The cumulative weight change is also shown in Figure 35. It shows that for the average sample, 55% of the mass is devolatilized below 800 C (45% remaining). The average ash content of the samples was 31%. Therefore, approximately 14% of the mass is fixed carbon, a typical number for biomass-type materials. In order to fully gasify the fixed carbon, high gasification temperatures and contact with oxygen or steam, as well as long residence times are helpful. Otherwise, some of the fixed carbon will remain in the ash. Pure cellulose, for comparison, is almost fully devolatilized at 400 C (>85%).

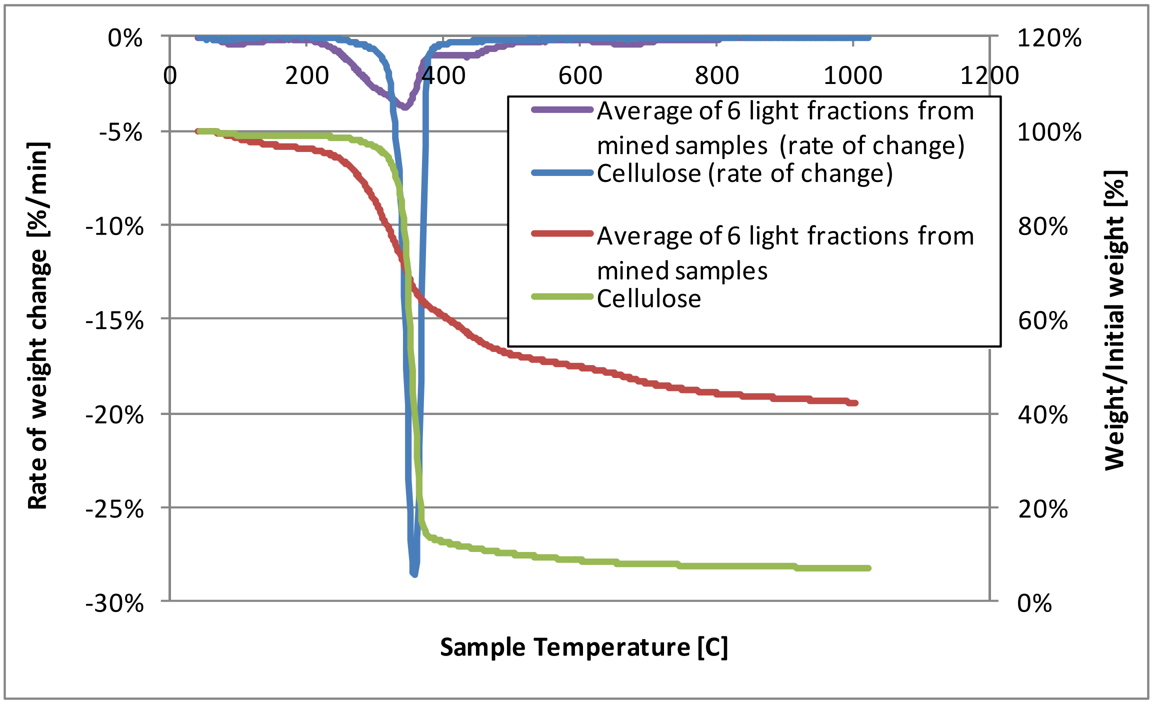


Figure 35: TGA results for landfill samples and cellulose. The weight and weight loss is shown as a function of temperature.

The tests up to 1000 C indicated no residues in the crucibles or phase changes from the output of the Differential Thermal Analyzer. This indicates that the melting point of all ashes is above 1000 C. Results from ASTM D 1857 are shown in Figure 36. The results show that the melting temperatures are lower in reducing atmospheres (relevant to gasification) than in oxidizing atmospheres. All characteristic temperatures were above 1100 C which meets the objective of 1000 C.

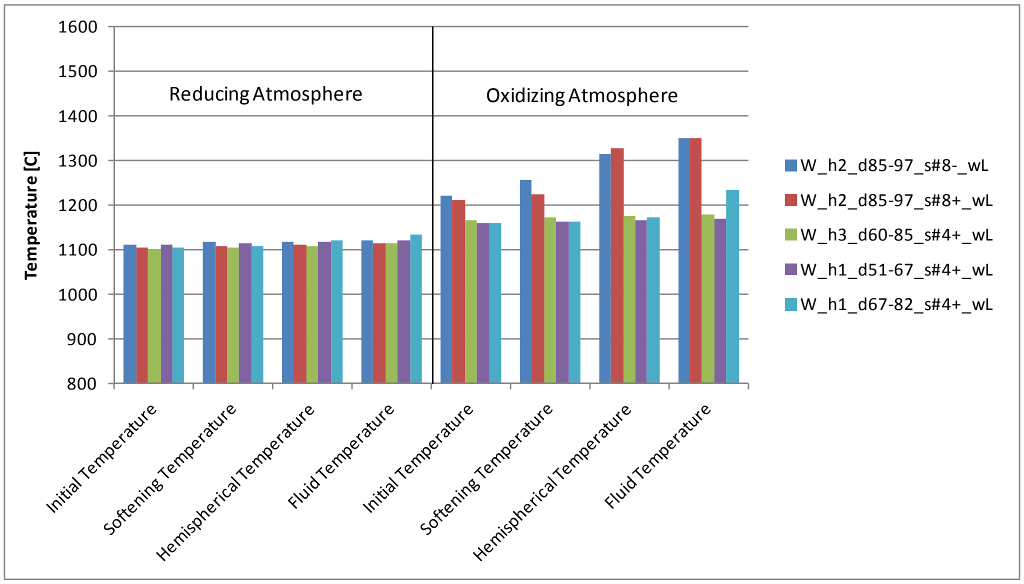


Figure 36: Ash-melting temperatures determined by ASTM D 1857 on several ash samples.

Objective 5: Estimate the total cost of methane per cubic foot and compare it with the market price for fossil and renewable natural gas. The objective is that methane will cost less than \$15/MMBtu, and less than \$5/MMBtu accounting for landfill cost reduction.

Pipeline-quality SNG can be produced from two pathways, the biogas generated from the anaerobic bioreactors and the produced gas from gasification of the mined landfill digestate. Figure 37 shows a schematic of the two pathways. Since a bioreactor produces biogas in sufficient quantities for approximately ten years and takes less than a year to fill, at least ten bioreactor cells need to be built. After ten years, the biogas production rate in the oldest cell has declined below feasible extraction levels and the residual solids can be mined while a new cell is simultaneously being filled. The biogas from the gas-producing cells (between one and nine years old) can be converted to methane by removing CO_2, polishing the gas of impurities, and compressing it to pipeline pressure. For this, some of the unit operations can be shared with the gasification-to-SNG pathway. Table 3 shows the quantities of waste and SNG for a landfill of consideration. About 30% of the waste in California can be processed when only landfills that have waste streams equal or larger than 4,268 tons/day (3,879 t/day) are considered. The table was updated with the results of the measurements of the mined samples. It shows that after removal of some recyclables, on a dry basis, 1,064 tons/day (968 t/day) are available for gasification. With an average energy content of 20 MJ/kg, SNG of 3,598,547 MMBtu/year, equivalent to approximately 3.6 billion cubic feet (BCF) per year of natural gas, could be produced from the gasification of the mined landfill digestate. This is slightly more than is produced from the biogas itself (3,033,485 MMBtu/year). Figure 38 shows a summary of the mass flows in the gasification pathway. The percentages of the flows are on a dry mass basis and all refer to the original 2,134 t/day retrieved from the mining of the bioreactor. Since the material contains large amounts of metals, other non-combustibles, and difficult to gasify materials such as PVC, it is advantageous to remove these materials for recycling before gasification. The costs of

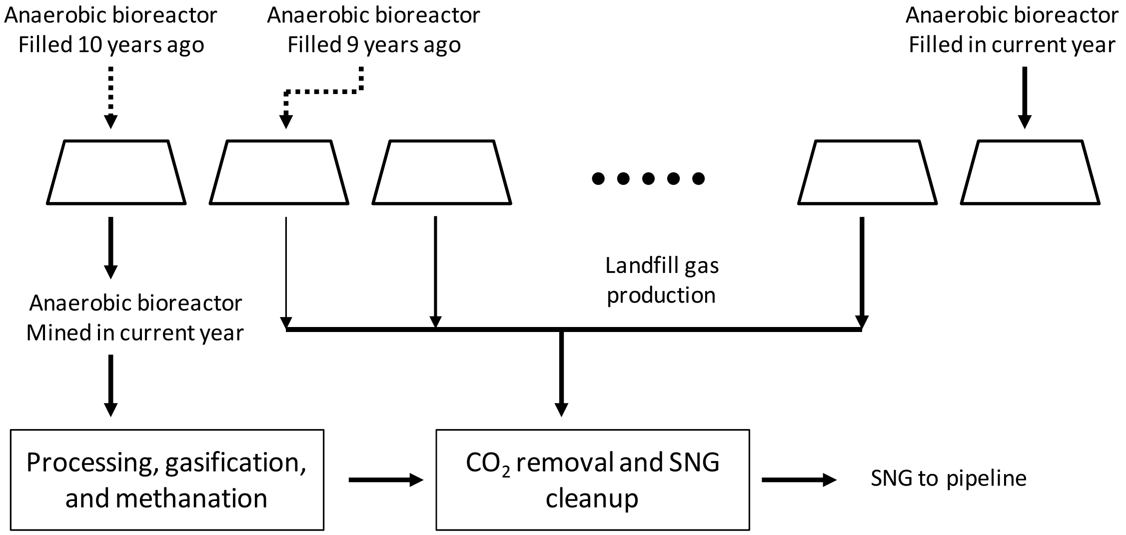


Figure 37: Chronological depiction of the anaerobic bioreactor. While one new bioreactor cell is filled, nine cells are producing landfill gas. The ten-year old cell has stopped gas production and is mined for recovering the landfill digestate for gasification.

Landfilled into bioreactor	3,879	t(wet)/day
Step 1: (Gas production from bioreactor)		
SNG produced (from landfill gas, 5% of mass)	194	t/day
Energy of SNG	112	MW(LHV)
Yearly production of SNG from biogas	3,033,485	MMBtu/yr
Step 2: (Gas production from residual material)		
Methane removed (during Step 1)	194	t/day
CO2 and other compounds removed (during Step 1)	582	t/day
Water added (during Step 1)	388	t/day
Wet digestate remaining (~40% moisture)	3,491	t/day
Dry digestate remaining	2,134	t(dry)/day
Removed during post recycling (~55%)	1,166	t(dry)/day
Digestate available for conversion	968	t(dry)/day
Energy content	20	MJ/kg
Energy potential	224	MW (LHV)
Energy into SNG (60% efficiency)	133	MW (LHV)
Yearly production of SNG from gasifaction of digestate	3,598,547	MMBtu/year

Table 3: SNG production from biogas and gasification at a midsized landfill

separating materials could be substantial, but some of it could be covered by the value of the reclaimed material. For example, retrieving ferrous and non-ferrous metals with magnets and eddy-current devices may generate the scrap metal value (~$10/ton if the waste contains 5% metals). Separating the fine fractions by weight in water (using the leachate) incurs the cost of re-drying the light fraction, but for this, as well as other feedstock drying, the waste heat from the gasification plant can be used. The advantage of using the fine fraction is, that it does not need to be shredded to proper size for the gasification plant as the large fraction will need to be. Some costs can be saved at the landfill for lower land requirements, monitoring and closure costs. But the savings are limited, since some of the waste materials from the separation processes and gasification will need to be landfilled again. Therefore, it is assumed that between costs and savings, $50 need to be paid for a ton of mined material before it reaches the gasification plant.

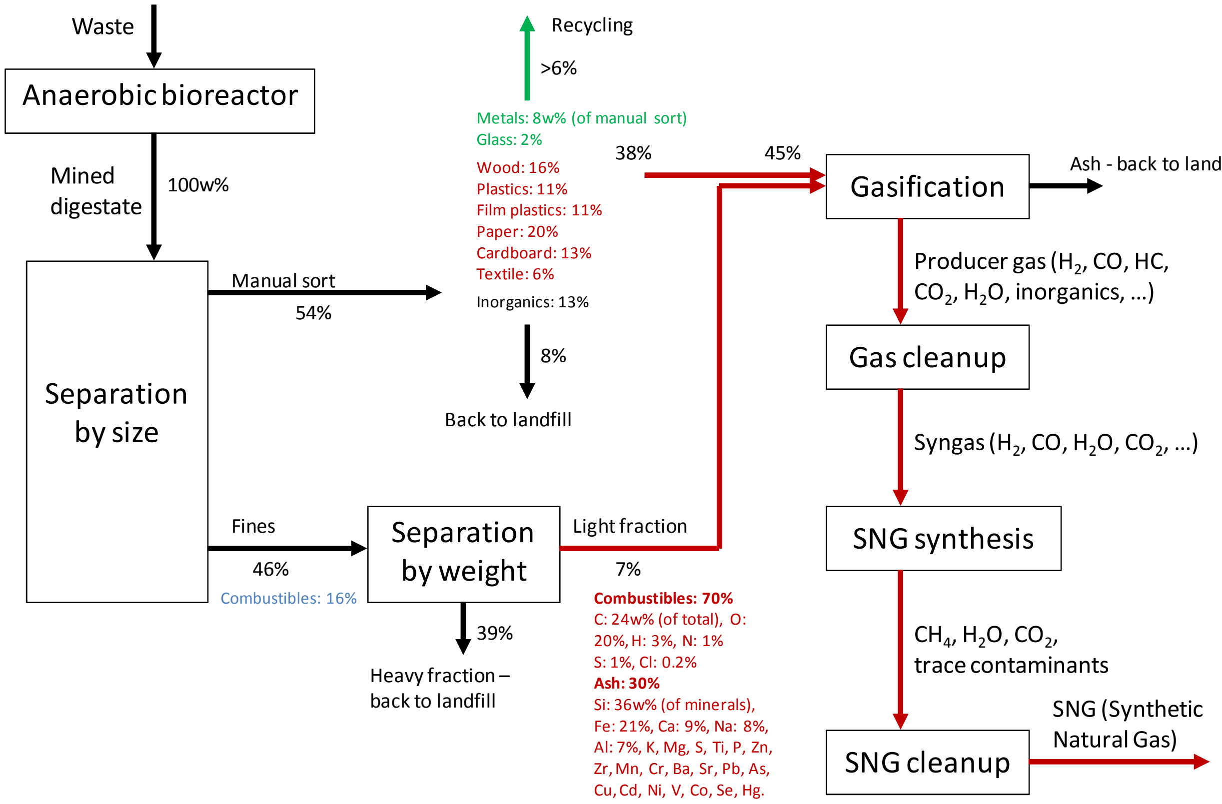


Figure 38: Pathway of mined landfill digestate to SNG

The capital and operating costs were estimated from two similar studies (DBFZ 2009, Progressive Energy 2010). The first study contains a very detailed analysis of biomass gasification with conversion to SNG. Since the landfill digestate is a more difficult feedstock, the capital costs were increased slightly. They are estimated to be $13.00/MMBtu (see Table 4), instead of the time-adjusted costs $12.00/MMBtu for the biomass plant in the DBFZ report. The Progressive Energy report details an oxygen-blown gasification plant in the United Kingdom for Solid Recovered Fuels. It shows a capital cost of $13.99/MMBtu, but it used a higher cost of capital and shorter lifetime.

The operating costs for the gasification and SNG synthesis are estimated to be $12.50/MMBtu which is in line with the DBFZ report once revenues for heat sales are subtracted. The Progressive Energy report shows a lower operating cost of $5.11/MMBtu, but it does not show all the detailed expenses the DBFZ report does. For the gasification and SNG synthesis, operating as well as capital costs are quite high, but not unreasonable for the number of chemical conversion steps required for gasification and gas cleanup. There are no large-scale demonstration plants of this kind which would be able to provide better estimates as well as document any cost reductions due to scale-up and learning curves.

The feedstock cost of $50/dry-ton translates into $4.44/MMBtu, which is much smaller than the capital and operating costs. The total cost of SNG produced by gasification and SNG synthesis amounts to $29.93/MMBtu.

The first part of Table 4 shows the costs for making methane from the landfill gas (biogas). Landfill gas is already widely used in SI-engines. In order to convert it to methane, first the opportunity cost of not making electricity needs to be considered. This is estimated as a fuel cost of $2.00/MMBtu. Next, the capital and operating costs of the CO_2 removal and gas cleanup need to be added. Warren (2012) shows an overview of various CO_2 removal processes in Europe and their costs. Most of them range at below $10/MMBtu except cryogenic technology which is listed at $20/MMBtu. The study also quotes another report (Urban, 2009) listing capital and operating costs for a 250 Nm^3/hr plant that employs either amine scrubbing or Pressure Swing Absorption (PSA). Since the current plant is much larger (11,300 Nm^3/hr), the specific costs are assumed to be by a factor two lower. This agrees with the cost projections for larger plant sizes by Warren (2012). The capital and operating costs then are $1.48/MMBtu and $4.18/MMBtu, respectively. The total cost of $7.66/MMBtu is more in line with current prices for natural gas.

If SNG is produced from both the landfill gas as well as the gasification pathway, synergies will arise since the size of some of the operating units will be even larger. In this case, a small portion of the landfill gas will still be burned in an SI-engine to provide electricity and heat for the gasification and cleanup steps. The overall costs of the combined production are $19.74/MMBtu. This does not meet the original objective of $15/MMBtu. Gains at the landfill level for saving landfill space were already included in the reduced feedstock costs. The main reasons for the high price of SNG are the high capital and operating costs of the gasification and SNG synthesis plant and the relatively low energy content of the digested landfill waste. The energy content could be increased by improving the separation of the fines or including more combustible materials that would otherwise be recycled, but it is assumed that recycling is generally more cost effective. All costs may come down once an actual demonstration plant is operated at a larger scale and the efficiencies of the waste excavation, drying, separating, and the gasification and SNG synthesis are documented. The operations may also include wastes from older dry-tomb landfills, but this is not considered in the current study.

The price of around $20/MMBtu for SNG does not include any carbon credits or other types of subsidies. These and the public benefit of reducing landfills may bring the costs closer to a reasonable range. It would also make California more self-sufficient in natural gas. In the 2001 California Electricity Crisis, natural gas prices were in the $20/MMBtu range (Weare, 2003).

Total Specific Costs - Biogas		
Levelized capital costs	$ 1.48	$/MMBtu
Operating costs	$ 4.18	$/MMBtu
Fuel cost (opportunity cost of not making electricity)	$ 2.00	$/MMBtu
Sum	$ 7.66	$/MMBtu
Total Specific Costs - Gasification of Digestate		
Levelized capital costs	$ 13.00	$/MMBtu
All operating costs (except fuel)	$ 12.50	$/MMBtu
Feedstock costs	$ 4.44	$/MMBtu
Sum	$ 29.93	$/MMBtu
Total Specific Costs - Biogas+Digestate		
Levelized capital costs	$ 7.73	$/MMBtu
Operating costs	$ 8.69	$/MMBtu
Fuel cost	$ 3.32	$/MMBtu
Sum	**$ 19.74**	$/MMBtu

Table 4: Specific costs for production of SNG from both biogas and gasification of the landfill digestate

Conclusions

Objective 1

The analyses of the samples from the aerobic reactor were completed as planned and found that the manually sorted fraction, the fine fraction, and moisture were 28w%, 32w%, and 40%, respectively. The carbon content in the fine fraction was less than 10w% and less than the objective of 15w%.

Objective 2

20 samples were successfully collected from the anaerobic bioreactors (5 locations and 2-5 different depths). The samples were classified into 8 different size groups, and the largest fraction was categorized into 12 different material groups. The manually sorted fraction was 42w%, the fine fraction was 40%, and the moisture was 18w%. The objectives were met except for the amount of the fine fraction which was below 70w%. Therefore, the manually sorted fraction should be included in an energy-conversion process.

Objective 3

Samples from the fine fraction from the anaerobic bioreactor showed 16w% combustibles (9w% carbon) which was less than the objective of 20w% carbon. A separation of a lighter fraction was performed so that this fraction (15w% by mass) contained 38w% carbon (70w% combustibles). The analysis of this fraction showed biomass-type material with 90w% biocarbon. The major inorganic elements were Si, Fe, Ca, Al, Na, Mg, K, and S. The fine fractions were analyzed for Cl and Hg which slightly failed the objectives because they were above the target levels of 1000 ppmw and 0.1 ppmw, respectively. Therefore, a reliable removal process of Hg is important. S and Cl will need to be removed during the process since they can impact catalysts or cause corrosion. The energy content of the mined landfill digestate from the bioreactor was estimated to be 9 MJ/kg, after subtracting a portion for recycling or incomplete separation. The majority of the energy content came from the manually sorted fraction and not from the fine fraction.

Objective 4

Several of the ground and weight-separated samples of the fine fraction were analyzed in a Thermo-Gravimetric Analyzer (TGA). The samples showed a large amount of volatiles to be released below 500 C, which makes them usable for gasification. Ash-melting temperatures were above 1100 C which would allow the material to be used in non-slagging gasifiers. Ashes containing a larger amount of Ca and Fe and lower amounts of Si had higher melting temperatures in oxidizing atmospheres.

Objective 5

Costs of production of SNG, both via landfill gas and gasification/synthesis were estimated based on similar projects and found to be \$7.66/MMBtu and \$29.93/MMBtu, respectively. For a combined production, the average cost would be \$19.74/MMBtu. The costs include a 9% real (above inflation) return on capital, and a reduced feedstock cost due to savings in landfilling. The major costs arise from the capital and operating costs of the separation, gasification, synthesis, and cleanup steps and are the reason that the cost objectives of \$5/MMBtu are not met.

Further Conclusions

Compared to fossil natural gas, producing SNG from biogas and landfill digestate is expensive. The current estimate shows that the pathway of gasifying the landfill digestate has costs more than three times higher than the pathway of just converting the landfill gas to SNG. Chemical synthesis is a major portion of the added cost, even though methanation is one of the more energy- and cost-effective methods. Creating electricity from the producer gas directly would save the cost for SNG synthesis, CO_2 scrubbing, and gas polishing. With this option, the landfills could still use the concept of anaerobic bioreactors and produce electricity from both the landfill gas and the digested waste. In this case, the digested waste could also be mined from existing landfills assuming a similar composition, which might not be true for older landfills. Using waste that has already been built up during the recent decades would allow building a gasification plant that is larger than one that would just accommodate the current rate of waste generation. This would bring down the capital and fixed operating costs per unit of output due to the large economies of scale that exist for these types of facilities.

The fine fractions that were analyzed during this study had a much lower energy content than the manually sorted fractions. This is in part, because it was more biomass based while the larger fraction contained also hydrocarbon-type of materials. The fines, however, have several advantages. They contain a high amount of renewable material. They would not need to be shredded since they are already small enough for typical gasifiers. There would most likely not be many other uses, since the separation for recycling may be expensive. A separation into a light fraction such as by water (leachate) would not need an extra classification by size, only a drying step. For the drying, waste heat from the gasification, synthesis, or electricity generation could be used and the effluent gas could be sent through a biofilter to absorb volatile contaminants.

The manually-sorted fraction had a relatively high amount of combustibles, since it contained non-degraded plastics. An energetic usage will compete with other recycling steps which may be more cost effective. Today, waste deposited into landfills has usually undergone significant extraction of recyclables, either at MRF facilities or at the household level, and not necessarily both. For each additional recycling step, the individual diversion rate decreases and the specific cost increases.

The estimated costs of gasification and synthesis are high, in part because there are few existing demonstration plants. Therefore, it is difficult to derive the cost reductions from building larger plants and from the technology improvements that would result from building subsequent plants. Improved technologies may be able to handle a larger variety of contaminants increasing the portion of usable feedstock. If these technologies, as well as the recycling technologies, improve further, energy could be derived from the waste directly, and only non-combustibles may end up in the landfills. But there are many closed as well as active landfills in California, and landfill mining may address them in the future. If the goals of reaching a large renewable content in the energy mix are further pursued, replacing fossil natural gas may be needed. In this case, the production of SNG as reported in this report may need to be pursued.

Recommendations

During the study, several additional tests were identified that would confirm some of the assumptions. For example it was mentioned that grinding with non-steel grinding media would confirm the amount of Cr in the sample. In general, some tests should be conducted on the ash produced from the finer fraction, since the trace elements are more concentrated than in the original sample. It should be determined if the ash would be a designated waste and if it needs to be placed in a Class II landfill. The ash should also be investigated with consideration of the new EPA leaching test method, Leaching Environmental Assessment Framework - LEAF (Garrabrants, 2010).

The heavy fractions from separating the fines using water were not analyzed. Since one third of the combustibles ended up in the heavy fraction, it would be of interest what type of combustible material it is and if it could be separated by other means. A large amount of the heavy fraction consisted of dirt, rocks, and glass and its contaminant level should also be determined since it will most likely be placed back into the landfill. Some of the materials could be used for daily soil cover. The water from the separation process should also be analyzed for water-soluble contaminants and compare it with the leachate in the bioreactors.

Since the manually sorted fraction had the highest amount of combustibles, this fraction could be analyzed more in detail. Among the plastic fractions, the determination of the fraction of PVC and other halogen-containing materials is recommended. The combustibles of the different manually sorted fractions (wood, plastic, film plastic, paper, cardboard, textiles) could also be for analyzed for ash composition in a manner similar to the fine fraction.

Deeper drilling into the anaerobic bioreactor is recommended to confirm whether the composition in deeper layers is similar to the ones measured in this study. While costly, there are techniques employing core drills that would be able to accomplish this. Such a study could be conducted in the different types of landfills, including the conventional dry-tomb types, to confirm that these landfills have a similar energy potential. A survey of landfills across the state should be undertaken to assess the total energy and materials potential represented by this resource.

Public Benefits to California

Although the cost of this technology is currently not competitive with natural gas, there are many potential benefits associated with the proposed technology. Landfills are currently viewed as a liability for communities, however, they can also viewed as potential future stored energy source waiting to be mined and converted to a renewable energy. Based on this study, the finer fraction of the waste was 85% to 95% biogenic. The manually sorted fraction was also 55% biogenic waste. Fuel produced from waste can lower California's dependence on fossil fuel imports. Reduction of greenhouse-gas emissions is also another benefit for California.

There are other indirect benefits to California such as: creation of jobs for manufacturing and operation of facilities, reduction in land use for landfill construction, increase in recycling and diversion from new and old landfills, and landfill closure and post-closure cost reduction.

To quantify the potential benefits, it is assumed that the cost of producing SNG at the landfill level reaches a break-even point. This would happen in a future scenario in which costs of production come down and fossil fuel prices increase. The remaining benefit to California's rate payers would then be the reduced landfill volume. The path of mining the landfill digestate for energetic conversion would reduce the size of the landfill by about 50%. This assumes that certain recyclables would be removed in the process, but that inorganic fractions and ash would be added back. On a yearly basis, the largest 30% of the landfills generate 6.5 million tons of digested landfill mass which could be reduced by 3 million tons. This does not count the benefits of accelerated decomposition in bioreactors or the mining of any existing landfills, or any technical solutions for the smaller landfills. The savings to the public lie in the externalities such as environmental benefits and long-term liabilities that are not covered by the operators of the landfills. Schollum (2010) shows a summary of estimated externalities for landfills in different countries. For modern landfills, the total externalities lie in the range of $13-$40 per ton of landfilled waste. They arise mostly from air pollution, water pollution, and greenhouse-gas emissions. If these external costs could be reduced by more than $10/ton through energetic usage, then the annual savings for California rate payers would be at least $30 million (3 million tons/yr reduction x $10/ton). The total socio-economic benefits could be several times larger if all of the above-mentioned indirect benefits are included.

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Glossary

TG/DTA	Thermogravimetric/Differential Thermal Analysis
ICP	Inductively Charged Plasma
LHV	Lower Heating Value
PSA	Pressure Swing Absorption
ppmw	Parts Per Million on a Weight basis
SLPM	Standard Liters Per Minute (at 1 atm and 273 K)
SNG	Synthetic Natural Gas
TGA	Thermo-Gravimetric Analyzer
XRF	X-Ray Fluorescence

Key for designation of samples:

W	West Cell
NE	Northeast Cell
h(number)	Sampling hole number
d(from)-(to)	Sampling depth in inches
s(screen size)	Size fraction retained by screen (# mesh size or opening in inches)
w(L/H)	Weight fraction (Light/Heavy)

Development Status Questionnaire

California Energy Commission **Energy Innovations Small Grant (EISG) Program** **PROJECT DEVELOPMENT STATUS**	**Questionnaire**

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Please Identify yourself, and your project: **PI Name** _Reinhard Seiser_**Grant** # __ 11-04G __

Overall Status

Questions	Comments:
1) Do you consider that this research project proved the feasibility of your concept?	*No, costs and technologies need to improve further to make SNG production competitive with natural gas.*
2) Do you intend to continue this development effort towards commercialization?	*No, although the production of SNG from landfill gas as well as gasification for electricity generation are less expensive alternatives.*
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	*Large scale demonstration projects of gasification, SNG synthesis, and gas cleanup have not been built yet.*
4) Have you defined a development path from where you are to product demonstration?	*No*
5) How many years are required to complete product development and demonstration?	*10 years to combine and improve the component technologies.*
6) How much money is required to complete engineering development and demonstration?	*Large-scale demonstration projects cost millions of dollars.*
7) Do you have an engineering requirements specification for your potential product?	*No*
Marketing	
8) What market does your concept serve?	*Municipal and private landfills.*
9) What is the market need?	*Need for landfill volume reduction and transition to renewables for greenhouse gas reduction*
10) Have you surveyed potential customers for interest in your product?	*No*
11) Have you performed a market analysis that takes external factors into consideration?	*No*
12) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*Exhaust emissions from drying, gasification, and gas cleanup, as well as toxicity of residual waste need to be below regulatory limits*
13) What is the size of the potential market in California for your proposed technology?	*30% of the largest landfills in California, accepting 10 million tons of waste per year*
14) Have you clearly identified the technology that can be patented?	*No*
15) Have you performed a patent search?	*No*

16) Have you applied for patents?	*No*
17) Have you secured any patents?	*No*
18) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*Findings were presented at Global Waste Management Symposium,Orlando, Florida June 22-25, 2014.*

Commercialization Path

19) Can your organization commercialize your product without partnering with another organization?	*No, industrial partners in waste separation, gasification and synthesis are needed.*
20) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*No*
21) Have you developed a commercialization plan?	*No*
22) What are the commercialization risks?	*The costs may be too high and the limits of purification may not be met.*

Financial Plan

23) If you plan to continue development of your concept, do you have a plan for the required funding?	*No*
24) Have you identified funding requirements for each of the development and commercialization phases?	*No*
25) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	*No*
26) What are the go/no-go milestones in your commercialization plan?	*N/A*
27) How would you assess the financial risk of bringing this product/service to the market?	*Very high because of the high capital costs and lack of demonstration projects.*
28) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	*No*

Public Benefits

29) What sectors will receive the greatest benefits as a result of your concept?	*Public sector for reduction of landfill volumes and greenhouse gas emissions.*
30) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*Savings in externalities may be worth $30 million/year if technology reaches break-even with fossil natural gas.*
31) Does the proposed technology reduce emissions from power generation?	*Yes, net greenhouse gas emissions of natural gas fueled devices.*
32) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*Toxins buried in landfill could reach water or atmosphere.*

Competitive Analysis

33) What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	*Landfill gas production from bioreactor is more mature technology than direct waste gasification.*
34) What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	*Extra cost of several separation steps compared to gasifying waste directly.*

Development Assistance

The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.

35) If selected, would you be interested in receiving development assistance?	*No*