# FEASIBILITY ANALYSIS OF GASIFICATION FOR ENERGY RECOVERY FROM RESIDUAL SOLID WASTE IN HUMBOLDT COUNTY


by

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**ABSTRACT**

FEASIBILITY ANALYSIS OF GASIFICATION

FOR ENERGY RECOVERY FROM RESIDUAL SOLID WASTE

IN HUMBOLDT COUNTY

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This analysis investigates the feasibility of implementing a gasification system to process residual solid waste in Humboldt County. The Humboldt Waste Management Authority manages 70,000 tons of municipal solid waste annually, which is transported over 180 miles for landfill disposal. This makes the cost of waste management three times higher than the national average.

Two alternative management scenarios were investigated as a way to reduce the cost and environmental impacts of waste disposal. This first scenario uses a solid waste material recovery facility to divert hazardous, recyclable, and compostable materials from the waste stream, landfilling only residual wastes. The second scenario locally processes separated residual waste for energy recovery using a gasification system. For this analysis, a plasma arc gasification system was selected from an evaluation of five companies offering a range of gasification technologies.

The results of this analysis indicate that implementing these management systems could reduce greenhouse gas emissions by more than 60% (17,400 metric $tCO_2e$/year). A material recovery facility could increase diversion up to 65% and reduce management costs by 5% ($226,000/year). Integrating a gasification system could increase landfill diversion to 99% and provide 3.4 MW of electricity capacity. This system could reduce management costs by 8% ($360,000/year) to 30% ($1,280,000/year) if electricity is sold at the higher renewable rate. This study demonstrates that developing waste as a resource is an opportunity to progress Humboldt County's energy, environmental, and economic security.

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## LIST OF ACRONYMS

BAF – Biogenic Accounting Factor
CAR – Climate Action Reserve
CARB – California Air Resources Board
CRV – California Redemption Value
Dirty MRF – Solid waste material recovery facility
EPR – Extended producer responsibility
GHG – Greenhouse gases
GWh – Gigawatt hour
GWP – Global Warming Potential
HBGS - Humboldt Bay Generating Station
HHV – Higher heating value
HHW – Household hazardous waste
HWMA – Humboldt Waste Management Authority
IES – International Environmental Solutions
IGMS – Integrated gasification management system
IGMS (NR) – Integrated gasification management system, without renewable energy classification
IGMS (PR) – Integrated gasification management system, with prorate renewable energy classification
IGMS (BD) – Integrated gasification management system, operating with biodiesel
IPCC – Intergovernmental Panel on Climate Change
IRR – Internal rate of return
IWM – Integrated waste management
IWT – Interstate Waste Technologies
LCC – Lifecycle cost
LCOD – Levelized cost of disposal
LFD – Landfill disposal scenario
LF P-MRF – Landfill disposal of post-sorted residual scenario
MMBtu – Million Btu, equivalent to 10 therms
MRF – Materials recovery facility
MSW – Municipal solid waste
$tCO_2e$ – Metric tons carbon dioxide equivalent
MWh – Megawatt hour
NPV – Net present value
RCRA – Resource Conservation and Recovery Act

RDF – Residual derived fuel
RPS – Renewable Portfolio Standard
PPD – Pounds per person-day
PV – Present value
RFI – Request for information
TPD – Tons per day
TPY – Tons per year
U.S. EIA – United States Energy Information Administration
U.S. EPA – United States Environmental Protection Agency
U.S. DOE – United States Department of Energy
UW – Universal wastes

# CHAPTER 1. INTRODUCTION

To call waste "trash" or "garbage" connotes it as something worthless or useless. This is a mistaken identity of municipal solid waste (MSW). The first municipal dump was created in Greece in 500 BC (Young, 2010a). Centuries later, burying waste continues to be the primary mode of waste disposal worldwide. Landfilling ignores the complexity of MSW, overlooking valuable materials and energy resources. Sanitary landfills have been engineered to alleviate some of the negative externalities of waste disposal using technologies like impermeable liners and gas collection systems. Even with these advancements, landfills continue to have a high environmental impact because they are a source of greenhouse gas emissions, predominately methane, and soil and water contamination (Manfredi et al., 2010). Other negative impacts include odor, litter, traffic, loss of valuable raw materials, and a waste management practice that supports a throw-away society (Wager, 2011).[1]

The goal of this study is to identify a viable MSW waste management strategy for Humboldt County. Humboldt County is located along the coast of Northern California. The area is densely forested, mountainous, and mostly rural with a population of 134,827 according to 2012 census data (U.S. Census Bureau, 2013). Humboldt County does not

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[1] Throwaway living was a term used first in 1955 as a title of an article, "Throwaway Living" in Life Magazine. The article promoted disposable items as a way to cut down on household chores ("Throwaway Living," 1955).

have an active local landfill, and therefore waste is transported over 180 miles away for disposal.

This study explores two advanced waste management technologies to identify viable alternatives to landfilling solid waste. The first technology is a solid waste material recovery facility to separate out divertible waste materials. The second technology and focus of this study is the feasibility of a gasification system to convert unrecoverable waste into marketable byproducts, including electricity.

This study investigates using a solid waste material recovery facility as way to manage the wide array of materials comprising modern day MSW. This type of facility would be able to separate solid waste into separate streams for individual management. This would allow materials like recyclables and compostable waste to be recovered at higher rates than relying on source separation by the public. Materials left over from this process which cannot be conveniently recycled or reused from an environmental and economic point of view are considered “residual waste” (Arena, 2012).

Installing a local gasification system is explored as an option for utilizing this residual waste. Gasification is a non-combustion thermal process that converts degradable waste into a combustible synthesis gas, or syngas, and a solid ash-like byproduct in a high temperature reactor with an oxygen-limited atmosphere. Syngas gas, composed primarily of carbon monoxide, hydrogen, and carbon dioxide, can be used to produce electricity in a Brayton cycle (gas turbine), Rankine cycle (boiler and steam turbine), or internal combustion engine. It is also possible to convert syngas to a liquid fuel, and other forms of storage and utilization of syngas are actively being researched (Bellomare & Rokni, 2013; Rezvani et al., 2012). In this way, gasification provides two services: waste disposal and energy recovery.

Gasification is an emerging technology for waste management, but more than 100 facilities are already in operation worldwide (U.S. DOE National Energy Technology Laboratory, 2010). However, only nine of these facilities are operating in the U.S., and most are in urban settings. This makes information about deployment of gasification in rural U.S. applications highly limited.

To identify a viable disposal alternative to landfilling, the performance of these technologies was analyzed using materials flow accounting, an assessment of greenhouse gas (GHG) emissions, and a lifecycle cost analysis to determine their compatibility of with the following waste management goals:

- reduce the environmental impact of MSW disposal,
- provide affordable waste management for the Humboldt community, and
- support local and state initiatives for waste reduction and diversion.

Multiple studies contain lifecycle analyses that find thermal conversion technologies a viable alternative to landfilling (Assefa et al., 2005; Jamasb & Nepal, 2010; Kaplan et al., 2009). These studies emphasize the importance of taking into account variables specific to each site and highlight the difficulty of providing generalized impact statements for disparate waste disposal methods (Gentil et al., 2010; Winkler & Bilitewski, 2007). There are several types of gasifiers used for solid waste processing, and there are multiple ways to utilize the energy recovered from waste. The performance variability created by these possible systems configurations contributes to a range of operational parameters that can be found in the literature (Youngs, 2011).

For these reasons, this feasibility analysis investigates deployment of a commercially available gasification system identified from a request for information with assumptions appropriate for Humboldt County. While the results of this study are not representative of gasification performance in all rural settings, they do demonstrate that advanced thermal technologies can be considered as an alternative waste disposal option for rural as well as urban settings.

# CHAPTER 2. BACKGROUND OF SOLID WASTE MANAGEMENT

Municipal solid waste refers to waste produced by residential, commercial, institutional, and industrial sources that managed by municipalities but collected and treated by both public and private entities. Examples of waste materials produced from these different sources are shown in Table 1. MSW typically excludes industrial and hazardous waste streams like municipal sludges, combustion ash, nonhazardous industrial process waste, construction, demolition wastes, and automobile bodies (Kollikkathara et al., 2009). The remaining mix of waste materials is often referred to as the waste stream.

Table 1. Examples of MSW sources and typical waste materials.

| | Sources | Typical Waste Stream Materials |
|---|---|---|
| **Residential** | Single family homes, duplexes, town houses, apartments | Food waste, newspapers, bottles, cans, plastics, and durable goods such as furniture and electronics |
| **Commercial** | Office buildings, shopping malls, warehouses, hotels, airports, restaurants | Office paper, disposable containers, florescent light tubes, food waste, and wooden pallets |
| **Institutional** | Schools, medical facilities, prisons | Paper products, food waste, film plastics, and medical sharps |
| **Industrial** | Factories, processing plants, refineries | Packaging, office wastes, lunchroom and restroom wastes, but not industrial process wastes that require special treatment |

Using the term “waste stream” conjures up an image of flowing water, a homogeneous, steady flow of material. However, the waste stream is quite the opposite, varying from state to state, county to county, kitchen to kitchen, and day to day. While data is often presented on the national level, it is important to realize that every place has a waste stream like a fingerprint: original, interconnected, and complex.

The U.S. has seen a dramatic increase in waste generation in the last fifty years. In 2010, Americans on average generated 4.43 pounds of trash per day. In the same year, the U.S. produced 250 million tons of MSW, compared to only 88 million tons in 1960 ( Figure 1). In the last ten years, the waste generation rate has leveled off. This may be due to a combination of waste diversion programs and declines in personal income related to the 2008 economic recession (Office of Solid Waste, 2010). Historically, waste generation is directly related to “degree of urbanization”, lifestyle, and economic growth; analysts predict that as the economy recovers waste generation will increase once more (Kollikkathara et al., 2009).

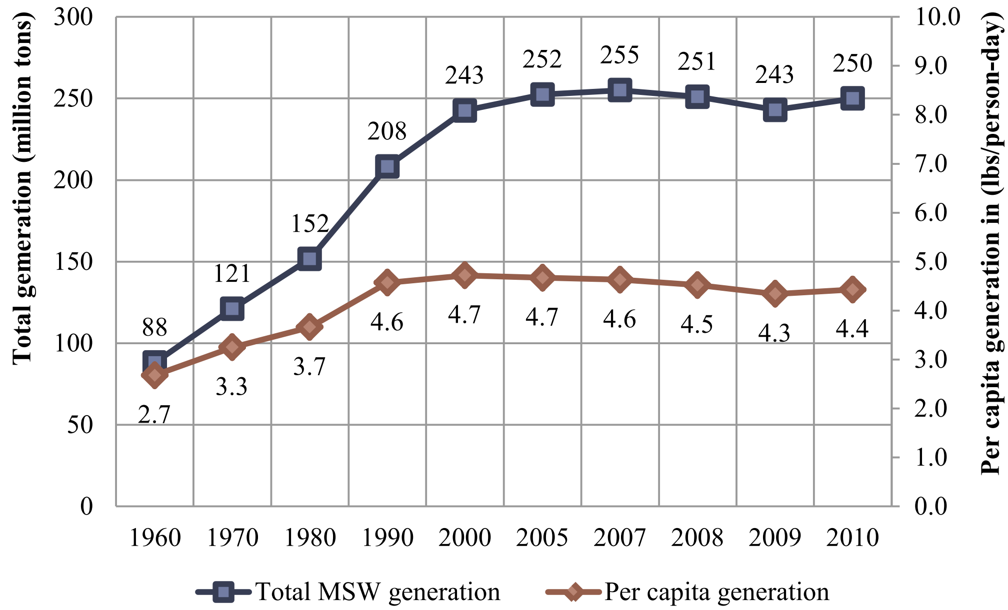


Figure 1. Waste production trends in the U.S. from 1960 to 2010. On left axis is U.S. MSW generation in million tons per year. On the right axis is U.S. per capita waste generation rates in units of pounds per person per day. Data source: (Office of Solid Waste, 2011)

The composition of the waste stream is as important as the amount of waste produced when evaluating waste management approaches. Like the volume, composition of the waste stream varies by scale and location. Identifying characteristics and trends in solid waste material flows is an essential tool for solid waste management planning. There are several classification methods but only the “material flow” method is included in this analysis as it is the most commonly utilized methodology, and was used in the Waste Characterization Study commissioned by Humboldt County (Cascadia Consulting Group & HWMA, 2012; Tchobanoglous & Kreith, 2002).

Material flow analysis identifies materials present in the waste stream by composition, such as paper, plastics, glass, metal, etc., using a methodology developed by the United States Environmental Protection Agency (US EPA) in the early 1970s (Tchobanoglous & Kreith, 2002). A characterization of the American waste stream in 2010, as described by the U.S. EPA is shown in Figure 2(a). Figure 2(b) shows the characterization of the waste stream in Humboldt County demonstrating that the national estimates are not necessarily representative of all communities. Even so, evaluation of national material flows can provide insights on general material flow trends.

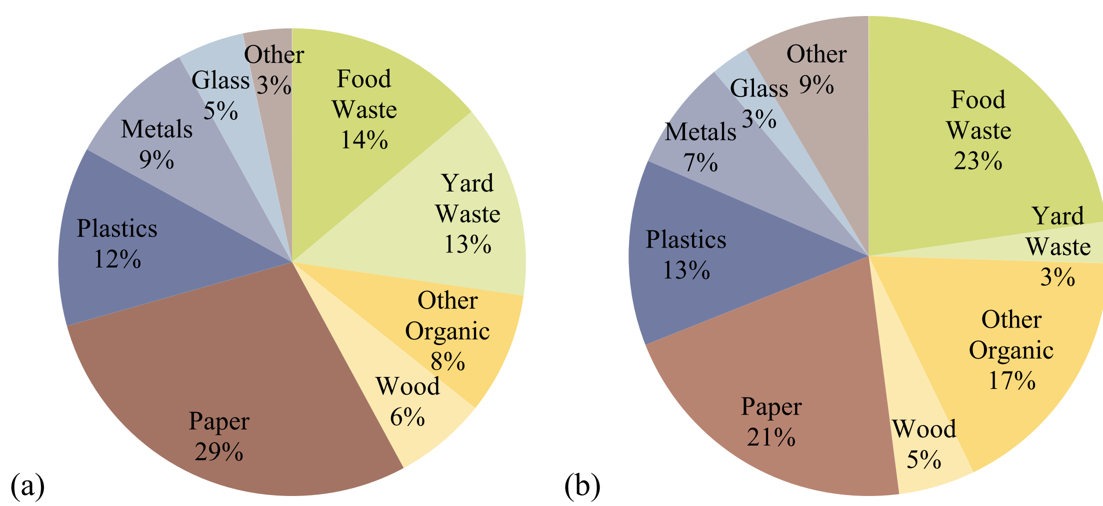


Figure 2. Comparison of (a) U.S. 2010 and (b) Humboldt County 2012 waste composition. While prevalence of some materials are similar, Humboldt County has a higher concentration of food waste and organics in the waste stream. Data source: (Cascadia Consulting Group & HWMA, 2012; Office of Solid Waste, 2011)

Performing characterization studies can be expensive and most communities, especially smaller communities, do not perform a characterization study on a yearly basis. HWMA has recently updated the County's Characterization Study, last performed in 1992. This latest Humboldt County waste profile provided the basis for the analysis that follows.

Another important distinction in material categorization is biogenic versus non-biogenic. The term biogenic refers to organic matter and non-biogenic refers to items made from fossil fuels or inert materials. Manufactured goods can complicate this seemingly straightforward distinction. Often manufactured products can contain as many as twenty different types of materials (Solid Waste and Emergency Response, 2002). Examples of these problematic objects include leather shoes with plastic soles, books bound with synthetic glues, and polyester blends. In the growing debate over MSW as renewable energy source, this biogenic distinction has become more significant.

Overall, the combined use of classification systems and waste production rates provide national and local governments with information needed to understand waste generation trends, which are vital to developing effective waste management plans. The sections that follow explore integrated waste management planning, disposal practices, and federal and California waste policies.

## 2.1. Integrated Waste Management Planning

Waste management is comprised of the collection, transport, processing, disposal, and monitoring of waste materials (Tchobanoglous & Kreith, 2002). Integrated waste management (IWM) is the application of a combination of waste management practices to minimize the health and environmental impact of waste disposal. IWM planning evaluates local needs and conditions in order to select the most appropriate management practices to create a comprehensive system.

The U.S. EPA has indentified four main practices to include in IWM planning. These include *source reduction*, which focuses on reducing the amount and toxicity of waste generated; *material recovery*,[2] which includes diversion practices of recycling and composting; *energy recovery*, which includes energy production from landfill gas, anaerobic digestion, incineration, or gasification; and *disposal*, which is most commonly accomplished by landfilling. Originally, the U.S. EPA promoted an interactive model that encouraged the general incorporation of four management areas in management planning (Tchobanoglous and Kreith, 2002). Later these practices were organized in to a hierarchal model that ranked the strategies according to environmental impacts as illustrated in Figure 3.

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[2] EPA refers to this management area as recycling and occasionally includes composting, but for clarification the term material recovery is used here to describe the recovery of both recyclable materials and nutrients from organic wastes.

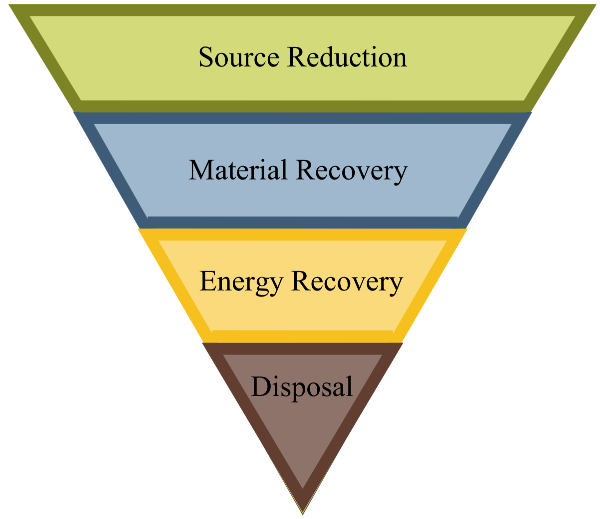


Figure 3. Diagram of hierarchical integrated waste management systems. The U.S. EPA hierarchical integrated waste management prioritizes management practices with lower environmental impacts. Figure adapted from: (U.S. Environmental Protection Agency, 2012a)

Source reduction and reuse is the most preferred method followed by material recovery, energy recovery, and lastly, disposal. This model is now used widely around the world and is the official planning model followed by many states including California (Solid Waste and Emergency Response, 2002). The next sections describe each of these practices in more detail.

### 2.1.1 Source reduction

Source reduction refers to reducing the amount of waste produced. Common examples of waste reduction practices include reusing or refurbishing materials, making different purchasing decisions, and modifying consumption patterns. Source reduction also emphasizes reducing the toxicity of the waste stream. Source separation of household hazardous waste[3] (HHW) and universal waste[4] (UW) for specialized disposal programs and reduction of the toxicity in manufacturing products are practices that support the objective of the this management strategy.

Source reduction also results in avoided emissions from reduced demand for raw resources, energy, and water used in the manufacturing process. It is estimated that for every pound of waste generated, 40 times more waste is created in the upstream processing stages, which is easily hidden by the global nature of industry (Walsh et al., 2006). A study from the University of California, Berkley, estimates that if California produced 40% less waste, GHG emissions associated with waste management would decrease by 6 million metric tonnes of carbon dioxide equivalent per year (Vergara et al., 2011). A large portion of this estimated emissions reduction is due to avoided manufacturing of the products that become waste.

This is why businesses and manufacturers can play a major role in source reduction. Product design can determine the useful life of an object, its reparability, reusability, and its toxicity. Design with these aspects in mind both extends the time before a product becomes waste and reduces the demand for new goods. Expanding

[3] HHW include substances like cleaning agents, aerosols, automobile fluids, herbicides, fertilizers, paints, solvents, adhesives, and pharmaceuticals.

[4] Universal wastes include materials like batteries, electronic devices, fluorescent lamps, and wastes containing mercury.

these product design considerations to include product packaging is another way that source reduction can be achieved. According to the U.S. EPA, disposal of containers and packaging make up 30% of the United States waste stream (Office of Solid Waste, 2010). Significant reductions in waste generation could be achieved by developing product packaging that uses fewer resources, can be easily re-used, and able to be recycled at the end of its useful life.

Education campaigns in the U.S. have a limited effect when used to achieve source reduction. This is evidenced in part by the historic increases in the waste generation rate that was stalled by the 2008 recession. Instead, incentive programs that encourage source reduction or waste diversion have been found to be more effective. One example is the "pay-as-you-throw" management strategy, which uses a variable pricing system where users are charged for the quantity of waste they produce on a mass or volume basis. Unlike the traditional fixed bill that does not vary with respect to the amount of waste produced, this payment method provides an economic signal to rate payers (Tchobanoglous & Kreith, 2002).

In some jurisdictions, regulation from the state or federal government reinforces local waste prevention programs. One effort administered by CalRecycle is Product Stewardship, also known as Extended Producer Responsibility (EPR), which targets disposal of problematic-toxic materials like carpet, paint, light bulbs, and batteries.[5] EPR shares responsibility for end-of-life product management with manufactures and all entities involved in the production chain by incorporating the costs of disposal into the total cost of the product. This provides a direct incentive to reduce or eliminate toxicity and waste through product design changes (California Department of Resources Recycling and Recovery, 2012a).

Source reduction is the least expensive waste management tool and can have the largest impact by preventing pollution and conserving resources. However, it can be the most difficult management strategy to implement from the position of a municipality since the most effective methods of source reduction are carried out by manufactures and waste generators (Tchobanoglous & Kreith, 2002).

### 2.1.2 Material Recovery

Material recovery includes practices of recycling and composting. The emphasis on recycling in education campaigns over the last 20 years has made it the most socially acceptable waste mitigation technique. From 1990 to 2010, recycling rates in the United States increased from 16% to 34% (Office of Solid Waste, 2011). The most common materials recycled in the U.S. are glass, metals, plastics numbers 1 through 5,

[5] California's Department of Resources Recycling and Recovery, known as CalRecyle, is the agency that regulates solid waste management activities in the state of California.

and paper products.[6] There are growing opportunities to recycle oil filters, batteries, latex paints, electronic waste, and other types of universal wastes.[7] The EPA estimates that in 2005 recycling reduced national GHG emissions by 49 million metric tons. However, the true benefits derived from recycling are varied and material dependent.

Manufacturing with some recycled materials like low grade plastics and paper products can be more expensive than using virgin materials (Subramanian, 2000). Conversely, recycling aluminum for instance, conserves more than 207 MMBtu per ton, the equivalent of 36 barrels of oil (Office of Solid Waste, 2010). For this reason, there is a strong market for recovered aluminum, and buyback programs are commonly available. In the case of recycling plastics, different types and grades of plastic make identification, separation, and purification challenging. This problem is compounded by the increasing quantity of plastic in the United State's waste stream; prevalence of plastics has increased 200-fold since 1960.[8] Plastics like polyethylene terephthalate or PET, labeled as number one plastic, are often down-cycled into secondary products or

[6] Plastics numbers denote different types of plastic resin. Plastic number1 is polyethylene terephthalate, typically used to make disposable water bottles. Plastic number 2 is high density polyethylene, which is used for milk jugs and grocery bags. Plastic number 3 is vinyl, which can be used for clear food packaging. Plastic number 4 is low density polyethylene, which is often used for squeezable bottles. Plastic number 5 is polypropylene, which is often used for yogurt and margarine tubs. Plastic number 6, polystyrene, and number 7, which is other or mixed, are not as widely accepted for recycling (Tchobanoglous & Kreith, 2002).

[7] The availability of these recycling services are often dependent on price balance between cost of collection, transportation, and preprocessing to the market price of recycled materials.

[8] In 1960, 0.4 million tons of plastics were thrown away compared to 31 million tons in 2010 (Office of Solid Waste, 2011; Tchobanoglous & Kreith, 2002).

lower grade plastic that is unrecyclable (Subramanian, 2000). Recycling plastic still saves about 50 to 75 MMBtu per ton compared with the production of virgin materials. Yet, the additional costs of transporting plastics to the few processing plants in the world pose an economic barrier since it is so inexpensive to produce plastic from raw materials (Solid Waste and Emergency Response, 2002).[9]

A number of states, including California, are mandating increased levels of recycling and encouraging curbside collection. Recycling that is collected this way is typically single or dual stream.[10] The collected recycling is separated at a material recovery facility (MRF) before being sold for reprocessing. Advances in mechanical sorting technology allow capture rates of up to 98% for some materials (Tchobanoglous & Kreith, 2002).

A solid waste material recovery facility, also called a "dirty MRF", employs mechanical and manual separation to remove recoverable materials from landfill-bound waste stream.[11] A dirty MRF can supplement or replace source separation. Currently,

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[9] Transportation of plastics has a cost inefficiency considering that most plastics are bulky and light, which causes them to take up more space when in transit, resulting in increased transportation cost per unit of mass, thus decreasing revenues from sale of the material which is also per units mass.

10 Dual stream has the fibrous recycling (paper and cardboard) separated from the container recycling (plastics, glass, and metals) while single stream has all these materials mixed together. There is much debate about which collection method is most effective. It argued that dual stream recycling produces higher quality raw materials since the paper is less soiled, but that single stream recycling increases participation because of simplicity (The Economist, 2007).

11 Examples of mechanical sorting equipment include: rotating trommels that separate materials by size; air classifiers which separate materials by density; magnets to remove ferrous metals; and glass clean up systems that recover glass cullet (Kessler Consulting, Inc., 2009).

there are six solid waste MRFs operating in California. These facilities are mostly utilized in metropolitan areas where there is limited landfill capacity. This has become a growing concern and the majority of these facilities were either installed or retrofitted in the last 10 years (Kessler Consulting, Inc., 2009).

Material recovery also includes the collection of wastes for composting. Biodegradable wastes, like yard trimmings and pre or post-consumer food waste can be converted into a soil amendment through a decomposition process. As a substitute for fossil fuel derived fertilizers, compost can offset up to 300 pounds of carbon dioxide equivalent per pound of wet waste or almost a ton of carbon dioxide equivalent when replacing peat (Boldrin et al., 2009).

Municipal scale composting systems are both space and time intensive. The process of making compost takes anywhere from three to eight months, depending on the management system and local climate (Tchobanoglous & Kreith, 2002). These requirements have led some waste management districts to consider advanced conversion technologies like anaerobic digestion.

Along with reduced raw materials and energy use, diversion is a value-adding activity that provides employment opportunities. Compared to other states in the U.S., California has the second-highest number of direct employment opportunities created by recycling and composting (California EPA Integrated Waste Management Board, 2003). It is expected that advancements in recycling technologies and product design will make more materials good candidates for recycling increasing material recovery and therefore jobs associated with recyclable material handling and processing. Even with these advancements, there will still be a fraction of the waste stream comprised of materials that are not recyclable.

### 2.1.3 Energy Recovery

Energy recovery from waste is achieved by a range of technologies including landfill gas recovery, anaerobic digestion, incineration, and gasification. Electricity production from captured landfill gas is the most widely implemented form of energy recovery in the United States. There are approximately 75 facilities producing electricity from captured gas in California with a total capacity of 299 MW (U.S. Environmental Protection Agency, 2012b). Typically landfill gas is composed of 57% methane, 42% carbon dioxide, 0.5% nitrogen, 0.2% hydrogen, and 0.2% oxygen, along with trace quantities of other compounds (Sethi, 2013). Some studies report that landfill gas collection is a better energy recovery strategy than incineration because materials like plastics and fibrous organics continue to provide carbon sequestration as they are effectively entombed in the landfill (Vergara et al., 2011).

Anaerobic digestion (AD) technologies provide both material and energy recovery in the form of compost and concentrated digester gas, which can be use to generate heat and electricity. These systems accelerate the biological decomposition process using heat and microbes to reduce the time needed produce compost and digester gas. Digester gas contains higher concentrations of methane than landfill gas and is a viable alternative for natural gas. Aerobic digesters are best suited to process wet biogenic wastes and are commonly deployed at wastewater treatment plants and dairies. AD is not as effective at processing woody biomass, which is more suited for other forms of composting or energy recovery (Bohn, 2010).

Incineration provides energy recovery by capturing thermal energy from combustible materials in the waste stream. Other byproducts include water vapor, char, fly ash, carbon dioxide, and hazardous gases such as nitrogen oxides, sulfur dioxide, particulate matter, carbon monoxide, acid gasses, lead, cadmium, mercury, dioxin, and furans (Kuo et al., 2008). Exhaust scrubbing technologies have improved over the years, dramatically cutting the pollution levels and emissions from incinerators (Young, 2010a). Even with these improvements, incinerators are still viewed by the public to be incredibly harmful to the environment. The majority of the incineration facilities in operation are on the east coast where there is a higher population density and less space available for landfill development (Michaels, 2011). Currently, there are only three municipal waste combustion facilities in California with a gross capacity of 640 MW (Stationary Source Division Emissions Assessment Branch, 2009).

Gasification is alternative form of energy recovery that uses a non-combustion thermal process to capture chemical energy from waste. In the last twenty years, gasification technologies like pyrolysis, conventional gasification, and plasma arc assisted gasification have gained more credibility on the world market (U.S. DOE National Energy Technology Laboratory, 2010). Gasification technologies capture chemical energy by heating feedstock waste materials in a low oxygen environment to produce a gas mixture of predominantly carbon monoxide and hydrogen, referred to as synthetic gas or syngas. The syngas, once cooled and cleaned, is a versatile energy source. Syngas can be combusted to produce heat and electricity in a Brayton cycle, Rankine cycle, or internal combustion engine. Syngas can also be converted to liquid fuels, and research is underway for using syngas in fuel cells (Bellomare & Rokni, 2013). Depending on the gasification process, the other marketable byproducts are fly ash and char, or slag, comprising one tenth of the original volume. The high temperatures of gasification reduces the leach-ability of these byproducts and can therefore be repurposed as an additive in a cement or construction aggregate (Young, 2010a).

### 2.1.4 Disposal by Landfill

Landfills remain the most common waste disposal method in the world. Types of landfills vary based on the materials they accept. Sanitary landfills are designed and operated to protect public health and minimize environmental impacts of MSW disposal. Monofill landfills provide disposal for individual materials like combustion ash or asbestos. Secure landfills are designated for the disposal of hazardous waste.

There are also different methods of modern landfilling. Most landfilling includes three basic steps of spreading waste in layers, compacting the waste, and then covering the waste with soil. Layers are successively stacked throughout the life of the landfill. When a landfill meets capacity, a more permanent cover is installed. Depending on the different fill methods, system design, and operations, landfill gas is collected at different capture efficiencies. While some modern landfill owners claim landfill gas capture rates as high as 95%, other environmental organizations estimate these rates to be closer to 20 to 40% (Stationary Source Division Emissions Assessment Branch, 2009).

As seen in Figure 4, the number of operational landfills has decreased substantially in the last 20 years, while the average landfill size has increased. While overall capacity is not an immediate problem, regional dislocations occur where waste is being transported long distances, as is that case in Humboldt County.

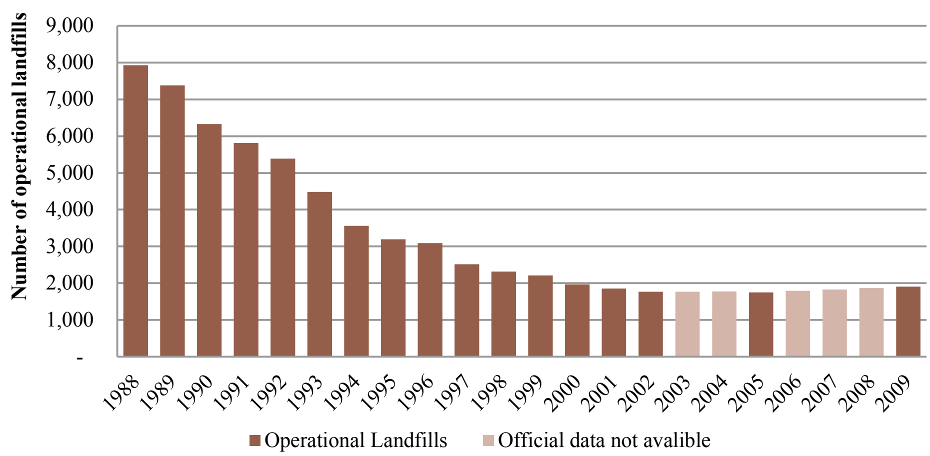


Figure 4. Number of operational landfills in the United States from 1988-2009. Interpolated figures are shown in light bars since official data was not available. Data source: (Office of Solid Waste, 2010)

Even with advancements in pollution prevention measures, landfills have a considerable environmental impact. Anaerobic decomposition of putrescent wastes produces high volumes of methane and volatile organic compounds that comprise landfill gas. This decomposition process can continue for hundreds of years depending on moisture conditions (Staub et al., 2010). Bacteria that assist in anaerobic decomposition produce acids that leach heavy metals into a solution that can become volatized or conveyed in the form of leachate. Leachate is created from the combining of liquid from the putrefaction of organic materials with water that percolates through the landfill such as rainfall, uncontrolled runoff, or water contained in the waste. Leachate run-off and leaks in collection systems can contaminate both soils and groundwater (Damgaard et al., 2011).

Not until a landfill is closed and gas collection systems are fully installed is it possible to capture all of the landfill gas. Depending on the climate conditions and landfilling methods, a batch of waste can continue to produce methane for 10 to 50 years, with more than half of these emissions released in the first two years (Tchobanoglous & Kreith, 2002). Landfill gas accounts for 2% of the U.S.'s total GHG emissions, mainly due to the production of methane (Kollikkathara et al., 2009).[12]

Electricity can be produced from landfill gas using internal combustion engines or gas turbines, but for small landfills, under one million tons of capacity, or if the landfill gas has a low methane content, infrastructure to produce electricity is cost prohibitive (Tchobanoglous & Kreith, 2002). In these cases, it is a common management practice to flare landfill gas, which breaks down methane and other trace gases including volatile

[12] Methane has 56 times more global warming potential than carbon dioxide on a time horizon of 20 years. Because of its 12 to 15 year atmospheric lifetime the global warming potential decreases to 21 over 100 years (United Nations Framework Convention on Climate Change, 2012).

organic compounds. In 2011, of the 279 landfills in California, 52 landfills were recovering energy from landfill gas and 128 were actively flaring (California Department of Resources Recycling and Recovery, 2013).

### 2.2. U.S. MSW Disposal Practices

Even though the hierarchical model for integrated waste management system is promoted on national and state levels, it does not reflect the actual waste disposal practices in the United States presented in Figure 5. As of 2010, a little more than one third of U.S. MSW was diverted for recycling or composting; 26% was recycled and composting diverted about 8%.

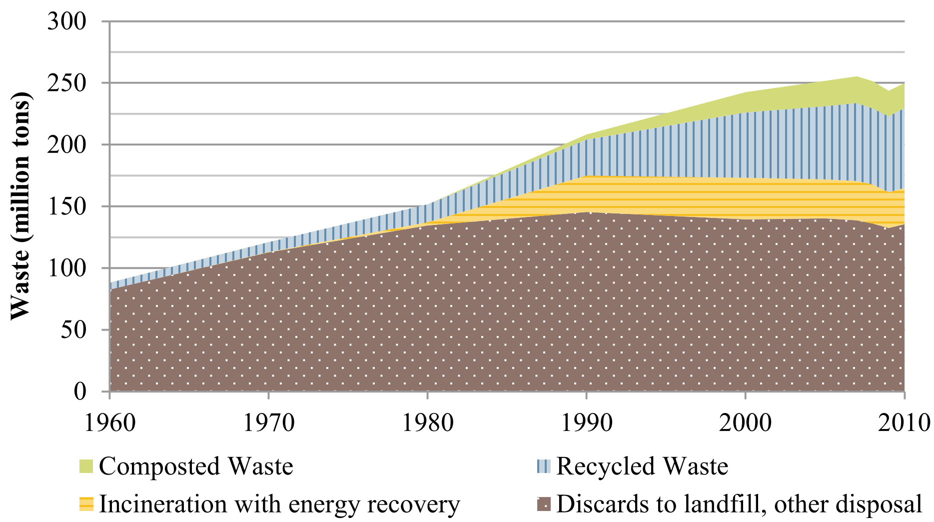


Figure 5. U.S. disposal method trends from 1960 to 2010. Figure shows ten-year averages from 1960 until1990, then annual data from 2000 to 2010. Data source: (Office of Solid Waste, 2011; Tchobanoglous & Kreith, 2002)

The prevalence of curbside yard and organic waste collection services has increased in urban areas, but predominantly only green wastes are composted on large scale. The yard waste capture rate is estimated to be 58%. In contrast, food waste was diverted at a rate of less than 3% nationally (Office of Solid Waste, 2011). Recycling has increased dramatically since 1980. Some states have created set recycling goals, but without changes to manufacturing of products and packaging, recycling is unlikely to exceed approximately 30% of the waste stream (California EPA Integrated Waste Management Board, 2003).

Incineration is an attractive MSW disposal option because it provides additional revenues from energy recovery. The first incineration facility came online in New York City in 1898 but growth in the industry did not accelerate until the enactment of the Public Utility Regulatory Policies Act in 1978. This Act required utility companies to purchase electricity produced by qualified small power production facilities at avoided cost.[13] This opened the market to many more energy recovery operations from waste (Hirsh, 1999). As a result, incineration capacity increased more than 10-fold from 1980 to 1990 from 2.7 million tons of capacity to 29.7 million tons (Office of Solid Waste, 2011).

As seen in Figure 6 this trend did not continue. There are currently 86 operational waste conversion facilities in the U.S., compared to the 186 that were operational in 1990. No new facilities were built from 1996 to 2007, due a combination of factors including economic constraints, emissions regulations, zoning and permitting

[13] This was implemented at the state level and therefore has varying levels of stringency (Hirsh, 1999).

restrictions, and public perception. This was due to a number of factors including larger landfill operations which increase competition for waste feedstocks, as well as the expiration of contracts under the Public Utility Regulatory Policies Act which caused facilities to lose tax credits (Office of Solid Waste, 2011).

Recycling and composting continue to be the most popular forms of landfill diversion. In 2010, the U.S. diverted 29 million tons of waste through recycling and composting programs, accounting for 12% of the municipal waste stream. In California, state lawmakers are setting ambitious diversion goals and costs of landfill disposal are increasing. This has many waste management agencies further investigating alternatives to landfilling waste, which includes both biogenic and MSW thermal conversion technologies (Alternative Resources, Inc., 2008; Predpall et al., 2005).

### 2.3. Policies Directing Waste Management

In the United States, local governments have historically addressed waste management needs. Cities or counties created their own waste policies, local transfer stations, and disposal sites. For many years, waste disposal was managed with little direction from national or state legislation to grow into a system that included cooperative effort of local government and privately operated companies. However, dramatic increases in waste generation, negative environmental externalities, and frequency of waste crossing state lines made regulation on the national level a necessity (Tchobanoglous & Kreith, 2002).

### 2.3.1 National Policies

The River and Harbors Act of 1899, was the first national piece of legislation addressing the environment or waste disposal. This act authorized the U.S. Army Corps of Engineers to issue permits for the disposal of waste into communal waterways, but was created more out of need to protect major routes of commerce than the environment. Ocean waste disposal was officially banned in 1972 (U.S. Environmental Protection Agency, 2013a). See Table 2 for a summary of major federal acts related to solid waste management.

From 1941 to 1945, recycling was initiated as a national effort to recover materials for the war. The prosperity period that followed this time provided a sudden increase in overall waste production making prominent the environmental impacts of waste disposal practices. The need to curtail these impacts resulted in the Solid Waste Disposal Act of 1965 (Kollikkathara et al., 2009). This act formally asked state and local governments to increase efforts of waste management planning by offering federal financial and technical assistance (U.S. Environmental Protection Agency, 2013b).

In 1970, the Solid Waste Disposal Act was amended to become the Resource Recovery Act, redirecting federal funds to material recovery, encouraging resource recovery facilities, and alternative disposal methods. This act was again replaced in 1976 by the Resource Conservation and Recovery Act. This Act required the removal of hazardous wastes, primarily industrial chemical waste, from the municipal solid waste stream (Kollikkathara et al., 2009). The latest amendment to the Resource Conservation and Recovery Act was in 1996 with the Land Disposal Program Flexibility Act which provided adjustments to landfill disposal restrictions of certain wastes and various other technical corrections to the Act (U.S. Environmental Protection Agency, 2013b).

Table 2. Major federal solid waste disposal, resource conservation, and recovery acts and amendments. Figure adapted from: (Tchobanoglous & Kreith, 2002) Additional sources: (Kollikkathara et al., 2009; U.S. Environmental Protection Agency, 2013b)

| Year | Act | Major Actions | Public Law Number |
|---|---|---|---|
| 1890 | River and Harbors Act | ▪ Required permits for dumping waste in communal waterways | |
| 1965 | Solid Waste Disposal Act | ▪ Initiate a national research development program for improved methods of solid waste disposal<br>▪ Encouraged waste management planning by offering technical and financial assistance to State and local governments | P.L. 89-272, title II |
| 1970 | Resource Recovery Act | ▪ Delineated hazardous waste from non-hazardous waste and sanitary landfills from open dumps | P.L. 91-512 |
| 1972 | Marine Protection, Research and Sanctuaries Act | ▪ Prohibited dumping of materials in the ocean including high-level radioactive waste, medical waste, sewage sludge, and industrial waste<br>▪ Provided guidelines for materials recovery | P.L. 92-532 |
| 1976 | Resource Conservation and Recovery Act | ▪ Set national goals for waste reduction through source reduction and recycling<br>▪ Gives authority of control over hazardous waste to U.S. EPA | P.L. 94-580 |
| 1980 | Comprehensive Environmental Response, Compensation and Liability Act | ▪ Established legal liability for remediation of abandoned hazardous waste sites<br>▪ Created a trust fund for cleanup activities<br>▪ Provided guidelines for the preparation of state solid waste management plans | P.L. 96-510 |
| 1984 | Hazardous and Solid Waste Amendments | ▪ Provided guidelines for the preparation of state solid waste management plans<br>▪ Phased out land disposal of hazardous waste<br>▪ Required closing of substandard landfills | P.L. 98-616 |
| 1996 | Land Disposal Program Flexibility Act | ▪ Provided some flexibility in the procedures for landfill disposal of certain wastes | P.L. 104-119 |

## **2.3.2 California Policies**

Federal guidelines for waste management assigned states more responsibility for solid waste management planning. Federal legislation like RCRA of 1976 gave states the authority to set regulations that were more stringent than the federal regulations, but it also contained specified directives such as closing open dumps and directing waste to sanitary landfills. These directives increased the cost of waste management without clear methods or guidelines for implementation. This and similar requirements resulted in local governments turning to state governments for assistance (Tchobanoglous & Kreith, 2002).

Following the Recovery Act of 1970, California passed the Solid Waste Management and Resource Recovery Act of 1972, which established the Solid Waste Management Board. This board provided policies to promote waste reduction, manage materials recovery, and protect public health and safety, and the environment. See Table 3 for a summary of major California State policies (Legislative Affairs Office, 2013).

In 1986, AB 2020 enacted the California Beverage Container Recycling and Litter Reduction Act. This Act, also known as the California Bottle Bill, created California's Beverage Container Recycling Program managed by the Department of Conservation. This program assigned a deposit fee to beverage containers that was added to the price of the product at point of sale.[14] These containers could later be returned to grocery stores or recycling centers to receive cash back according to the California Redemption Value (CRV). [15] The goal of the program was to achieve an 80% recycling rate. The first year of implementation the recovery rate was 55% and by 2009, the 80% goal was met. In 2012, the recovery rate for beverage containers was 84% (California Department of Resources Recycling and Recovery, 2012b). The CRV cash incentive is attributed to recycling 272 billion aluminum, glass, and plastic beverage containers since the start of the program in 1987 (Division of Recycling, 2007).

The Integrated Waste Management Act of 1989, California Assembly Bill AB 939, drafted by Assembly Member (now Senator) Byron Sher, replaced the Solid Waste Management Board with the California Integrated Waste Management Board. AB 939 also set waste diversion goals for local jurisdictions of 25% from each city and county by 1995 leading up to 50% diversion by 2000. Under this bill, fines were issued to counties that fell short of these diversion rates, further enforcing these goals. There were some exemptions made to cities that incinerated of 75% or more of their solid waste and it could be proven that these diversion goals would impair existing contracts or

[14] A deposit is paid into the California Beverage Container Recycling Fund by beverage distributers on every beverage for sale in California. Beverage distributers pass on this fee to the retailer, who in turn passes it to costumers at point of sale (Division of Recycling, 2007).

[15] The California Redemption Value (CRV) has increased from when it was enacted from $0.02 to $0.05 for containers less than 24 ounces, and from $0.08 to $0.10 for containers 24 ounces or larger (California Department of Resources Recycling and Recovery, 2012b; Division of Recycling, 2007).

reduce the ability to repay loans used to finance the project. Also upon specified conditions up to 10% of waste thermally converted could go towards these diversion goals (Legislative Affairs Office, 2013).

By 2005, the state waste diversion rate had increased from 10% when the California Integrated Waste Management Board was established to 52% (Stephens, 2012). That same year the California Integrated Waste Management Board was replaced by Department of Resources Recovery and Recycling, known as CalRecycle, and moved into the Natural Resources Agency. This brought the state's recycling and waste management programs under control of a single department. CalRecycle has the goal of creating the highest waste reduction recycling and reuse goals in the nation (Legislative Affairs Office, 2013).

Other California legislation has provided directives for reducing the impacts from waste management. One example is the AB 32 Global Warming Solutions Act signed by Governor Schwarzenegger in 2006. This Act was the first legislation to comprehensively cap emissions across economic sectors. AB 32 stipulated that by 2020 California would reduce GHG emissions to 1990 levels and by 2050 achieve 80% reduction from 1990 levels. The California Air Resources Board (CARB) of the California Environmental Protection Agency developed a scoping plan to identify reduction measures needed to meet the 2020 reduction target. The Scoping Plan, adopted in 2011, includes a cap and trade scheme, goals for renewable energy capacity, and directives for waste management (Raymond, 2013).

Table 3. Summary of California solid waste disposal and resource conservation and recovery acts. Figure adapted from: (Tchobanoglous & Kreith, 2002) Additional sources: (Legislative Affairs Office, 2013; Raymond, 2013).

| Year | Act | Major Actions | Chapter Number |
|---|---|---|---|
| 1972 | Solid Waste Management and Resource Recovery Act | ▪ Established the Solid Waste Management Board<br>▪ Required the Board to conduct studies on new or improved methods of solid waste management | Chapter 342, Statutes of 1972 |
| 1986 | AB 2020 California Beverage Container Recycling and Litter Act | ▪ Created the California's Beverage Container Recycling Program to be managed by the Department of Conservation | Chapter 1290 |
| 1989 | AB 939 The Integrated Waste Management Act | ▪ Established an integrated waste management hierarchy as a guide for the Board and local agencies<br>▪ Replaced the Solid Waste Management Board with the California Integrated Waste Management Board<br>▪ Set waste diversion mandates of 25% waste diversion by 1995 and 50% waste diversion by 2000<br>▪ Established a comprehensive state-wide system for permitting, inspections, enforcement, and maintenance for solid waste facilities | Chapter 1095, Statutes of 1989 |
| 2005 | SB 63 Waste Management Act | ▪ Created the Department of Resources Recovery and Recycling (CalRecycle) within the Natural Resources Agency to replace the California Integrated Waste Management Board | Chapter 21 |
| 2006 | AB 32 Global Warming Solutions Act | ▪ Set goals for GHG emission reductions to 1990 levels by 2020 and a further 80% reduction by 2050<br>▪ Called for a Scoping Plan from CARB for meeting reduction goals | Chapter 488, Statutes of 2006 |
| 2011 | AB 341 Mandatory Commercial Recycling | ▪ Set waste diversion goal of 75% waste diversion by 2020<br>▪ Requirements of mandatory recycling from businesses | Chapter 476, Statutes of 2011 |

The cap and trade program in California started at the beginning of 2012 with enforceable compliance obligations, beginning in 2013, for sources responsible for 85% of California's GHG emissions. Responsible entities include major sources of GHG emissions in the state such as refineries, power plants, industrial facilities, and transportation fuels. Caps were set at 2% annual reductions of forecasted emissions for the first two years, increasing to 3% reductions from 2015 to 2020. Offsets are limited to emission-reduction projects in the U.S. and were initially restricted to four areas: forestry, urban forestry, dairy digesters and destruction of ozone-depleting substances (California Air Resources Board, 2011).

The Scoping Plan also calls for a Renewable Portfolio Standard (RPS) administered by the California Public Utilities Commission. The California RPS program was first established in 2002 with the goal of increasing the renewable energy in the state's electrical grid mix by 20% by 2017. In 2011, this target was increased to a 33% by 2020 (California Public Utilities Commission, 2007). Since 2003, renewable capacity of 4,989 MW of has come on-line under the RPS program, and as of 2012, 19.8% of electricity consumed in California was from RPS-eligible sources (California Public Utilities Commission, 2013).

While digester gas and energy recovered from biogenic waste are widely accepted sources of renewable energy, there is a debate as to whether energy derived from mixed MSW should be considered renewable since it can include materials produced from fossil fuels. Because of this disagreement, renewable eligibility for thermal conversion of MSW is not recognized on a national level. California eligible renewable energy sources include landfill gas, digester gas, biomass, and in some cases MSW (California Public Utilities Commission, 2007). The Renewable Portfolio Guidebook lists criteria for MSW eligibility including: acceptable levels of recycling recovery and conversion by a gasification process (California Energy Commission, 2012). For excerpts of criteria, see Appendix A.

Also within the AB 32 Scoping Plan are recommendations specific to the waste sector. Actions called for include reduction of methane emissions at landfills, increased waste diversion, composting and other beneficial uses of organic materials, and mandated commercial recycling. The Scoping Plan also recommends expanding programs that focus on consumer demand, manufacturing and movement of products. This includes implementation of programs like Extended Producer Responsibility (EPR) for more products and promoting environmentally preferable purchasing. These actions were all part of an effort to move towards a system where all MSW can be recovered or composted, otherwise known as zero waste (California Air Resources Board, 2008).

In 2011, AB 341 was passed creating a statewide mandatory commercial recycling program implemented July 1, 2012, in response to the recommendations of the AB 32 Scoping Plan. AB 341 increased California's waste diversion goal to 75% by 2020. This legislation was designed to achieve a 5 million metric ton reduction in carbon dioxide equivalent emissions (Legislative Affairs Office, 2013). AB 341 also amended the definition of diversion to no longer include alternative daily landfill cover or thermal processing.[16] AB 341 uses a different metric of pounds per person per day

[16] This new definition reduces the statewide 2012 claim of 65% landfill diversion to 49% (Edgar & Associates, Inc., 2012).

(PPD) that is more descriptive and easier to calculate than the percent based diversion used previously. This Assembly Bill also establishes a new baseline determined from the average disposal rate from years 2003 to 2006 instead of from 1990 to 2010. This changes the baseline to 12.6 PPD from 10.7 PPD, and targeted disposal rate at 2.7 PPD (Edgar & Associates, Inc., 2012).

California continues to be at the forefront of progressive policies for environmental protection and waste reduction. However, implementation of these policies and metrics for measuring success is often hampered by diverse interpretations of new legislation and difficulty obtaining permits. These challenges apply especially to implementing gasification as an emerging waste management technology.

# CHAPTER 3. SOLID WASTE GASIFICATION

Gasification is a thermal process that has been in use since the 1800s. At that time, coal and peat served as the gasification feedstock to produce town gas that was piped into cities and homes for lighting and cooking. During World War II, small-scale gasifiers were developed to power vehicles, boats, trains and electric generators. Demand for town gas was eventually replaced with electricity and natural gas.

It was not until the 1980s that MSW was used as a feedstock for gasification. The first commercial sized MSW gasification system was installed in Japan in 1979 processing 100 short tons per day (tpd). By 1980, Germany installed a 154 tpd facility using pyrolysis to process MSW and sewage sludge, also known as municipal sludge (Engineering-Center for Environmental Research and Technology, 2009).

Energy recovery from waste has been recognized as an essential part of a sustainable integrated waste management system (Arena, 2012; Psomopoulous et al., 2009). It has been found that gasification can meet environmental air quality standards when implemented properly. Also, communities with energy recovery systems as part of their waste management plan achieve higher rates of recycling (Achillas et al., 2011; Youngs, 2011). The major advantages of gasification are: reduced land use, 100 times lower than required for landfilling over 10 years; modular design allowing for gradual scaling and faster installation than incineration; suitability for smaller applications; and production of syngas as a secondary product, which allows for intermediary clean up before it is converted into final energy products.

## 3.1. Gasification Processes

Gasification uses a thermal process to capture chemical energy from feedstocks. There are three main classifications of gasification processes, characterized by the reactor temperature. Pyrolysis occurs at lower temperatures between 500°C and 800°C and its distinguishing characteristic is that feedstock is processed in the absence of oxygen. Conventional gasification, is thermal processing at temperatures between 550°C and 1600°C, depending on the air mix used in the reactor chamber (Arena, 2012). Plasma assisted gasification or plasma arc gasification uses a plasma field of electrically charged gas to reach temperatures of 4,000°C to 7,000°C. At these high temperatures, plasma arc systems experience more feedstock flexibility, achieve higher thermal efficiencies, and produce cleaner syngas (Young, 2010b). The rest of this section will discuss the advantages and disadvantages of each of these systems in more detail.

### 3.1.1 Conventional Gasification

Some conventional gasification systems require that waste is preprocessed to achieve more even feedstock heating and higher conversion efficiencies. Preprocessing of MSW can include removal of un-reactive materials like glass and metal, shredding to create a smaller, uniform fuel material, drying to remove moisture, or pelletization. Processed MSW is referred to as residual derived fuel (RDF). A diagram of a conventional gasification process is shown in Figure 6.

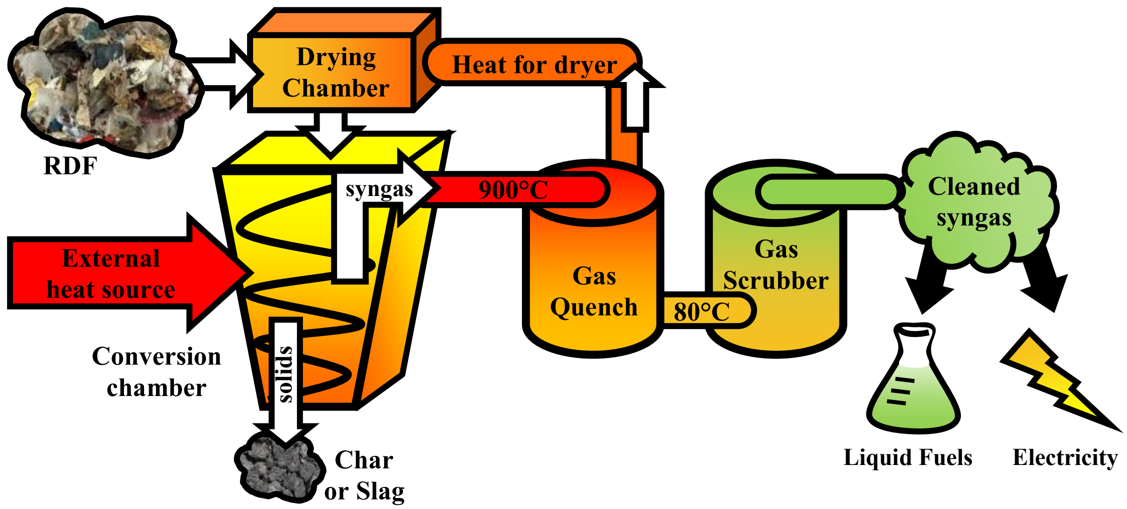


Figure 6. Diagram of conventional waste gasification system. Prepared residual derived fuel (RDF) enters the conversion chamber where it is heated to release synthesis gas, which is primarily composed of carbon monoxide and hydrogen. This syngas is cooled and cleaned before being converted into liquid fuels or combusted to produce electricity and heat.

In a typical gasification system, prepared waste or RDF is fed through a drying chamber and then into a pressurized, oxygen limited conversion chamber and heated from an external heat source. High moisture levels in feedstock lead to increased production of tars at the reactor outlet (Luo et al., 2010). This thermal decomposition process produces synthesis gas, also called syngas. The direction of material flows and heat distribution designate different gasifiers. Down draft or up draft gasifiers with stationary or fluidized beds are just some of the available conversion chamber configurations (Arena, 2012).

The original volume of the feedstock is reduced by 75% to 95% and the remaining solids exit the conversion chamber as char or vitrified slag depending on the temperature of gasification. Both char and slag are marketable materials which can be repurposed for industrial processes like cement production or as aggregate for other construction materials (Jung et al., 2005).

Syngas is composed of a combination of carbon monoxide and hydrogen with the presence of methane, carbon dioxide, nitrogen, and trace contaminants. Syngas is collected from the conversion chamber to be cleaned and cooled before it is converted into secondary forms of energy like electricity or liquid fuels. Syngas has a similar composition to natural gas and can be combusted in a combustion engine, Brayton cycle, or Rankine cycle to produce electricity (Arena, 2012). The other common utilization of syngas is conversion into liquid fuels via a Fischer-Tropsch reaction to produce an alternative to conventional transportation fuels (U.S. Department of Energy, 2012). Additionally, new studies are identifying ways to use syngas to generate electricity in fuel cells (Bellomare & Rokni, 2013; Youngs, 2011).

While product gases from gasfication can include air polluants such as particulate matter, aerosols or tars, nitrous oxides, sulfur oxides, dioxins and furons, and hydrocarbon gasesm there are mulitple points of intervention avaliable for controlling emissions because gasfication produces a secondary energy product. Gasification systems can employ pollution control systems at the reactor outlet as well as the exhaust gas outlet. See Figure 7 for a comparision of emissions from the combustion of syngas compard to U.S. EPA pollution standards (Davis, 2011).

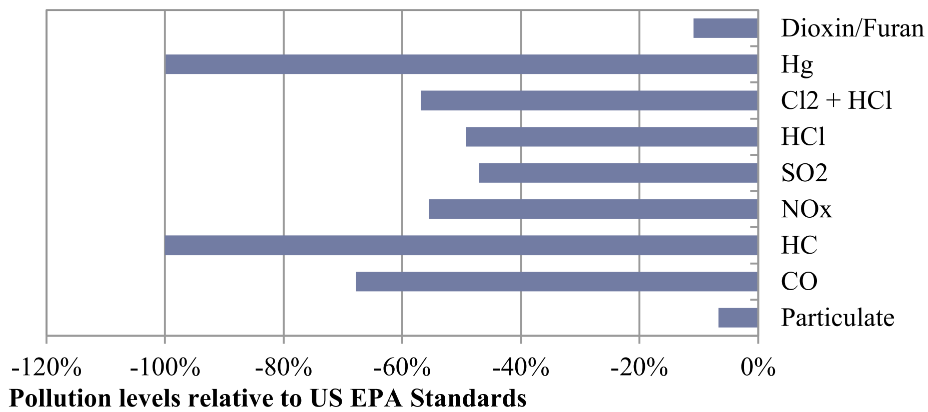


Figure 7. Production of air pollutants from combustion of syngas from MSW compared to U.S. EPA standards. Data source: (Davis, 2011)

A 2009 study produced by the University of California, Riverside determined that the pyrolysis and gasifciaton facilites, currently operating at the time, met emission limits mandated in California, the United States, and the European Union with only a few exceptions. In every gasifcation process evaluated, levels of toxic air contaminants of dioxins, furon and mercury met the most stringent standards worldwide. This study concluded that advancements of air pollution control strategies and equiment in the last ten years have made emissions control of thermochemcial conversion process no longer a technical barrier (Engineering-Center for Environmental Research and Technology, 2009).

### <u>3.1.2 Pyrolysis</u>

Pyrolysis takes place lower temperatures in the absence of oxygen and produces intermediate products of syngas, pyrolysis oil, and char. Pyrolysis has been used extensively in manufacturing to produce products like coke for steel processing and industrial chemicals (U.S. DOE National Energy Technology Laboratory, 2010). A drawback of this process in the high level of preprocessing required when treating MSW. Uniform densities, feedstock sizes, and moisture levels greatly influence the conversion efficiency of these systems (Luo et al., 2010).

There are two main types of pyrolysis processes, “slow pyrolysis” and “flash pyrolysis”. Slow pyrolysis takes place in a stationary reactor and used to maximize the production of gas and solid byproducts. Flash pyrolysis occurs over several minutes and is used primarily for producing pyrolysis oils (Lamers et al., 2013).

Syngas from pyrolysis contains methane, as well as carbon monoxide, hydrogen, carbon dioxide and water. Pyrolysis can produce high amounts of tar which damages generation equipment and clogs syngas filters designed to remove other pollutants (Arena, 2012). The char and ash produced from pyrolysis can have varying levels of toxicity. Disposal of char from pyrolysis range from combustion as a secondary heat source, repurposing as a cement additive, to specialized disposal in a monofill (CH2MHill, 2009).

### 3.1.3 Plasma Arc Gasification

Plasma arc gasification is the newest development in waste gasification technology. Also referred to as plasma assisted gasification, plasma produced from electricity provides the heat source for the gasification process. Plasma is a stream of high voltage, high current electricity produced from a plasma torch, and has characteristics similar to lightening (Young, 2010b). The plasma field reaches temperatures up to 14,000°C. Even a few feet from the torch temperatures can be as high as 2,700°C to 4,400°C (Ducharme, 2010). These extremely high temperatures break down waste more completely giving plasma gasification systems increased feedstock tolerance and higher syngas yields than traditional gasification while producing less char and tar (Arena, 2012; Luo et al., 2010). In some systems, syngas is passed through a secondary plasma field for additional cleaning. The solid byproduct of this system is vitrified slag or glassy slag, which exceeds EPA leach test standards (Murphy & McKeogh, 2004).

The oldest operating plasma arc facility is located in Japan. It was commissioned in 2002 by Hitachi Metals and uses a Westinghouse Plasma Corporation plasma gasification process. The largest plasma arc facility has a processing capacity of 274 tonnes of MSW per day (Engineering-Center for Environmental Research and Technology, 2009). Plasma arc gasification is growing in popularity because it has more flexible feedstock acceptability, can produce cleaner syngas, and achieves higher electrical efficiencies compared to conventional gasification (Arena, 2012; Young, 2010a).

## 3.2. Advantages of Gasification Over Incineration

While incineration is recognized globally as the most proven technology for thermal processing of MSW, many municipalities are recognizing benefits of gasification over incineration (Alternative Resources, Inc., 2008b; Engineering-Center for Environmental Research and Technology, 2009). Incineration produces electricity strictly through a direct combustion process producing thermal energy, while gasification is able to capture the chemical energy potential of waste products in the form of syngas.[17] See Table 4 for a comparison of different waste thermal conversion technologies.

The syngas produced by gasification is versatile and can be used for energy storage and power generation (Jenkins & Williams, 2006). This difference allows gasification to capture energy content from waste at a higher efficiency especially when a heat load is absent. Gasification is a more efficient source of electricity, even when taking into account the higher parasitic loads of gasification, required as an external heat source. This is especially true for plasma arc gasification, which has an even higher internal energy demand but performs at net higher efficiencies (Young, 2010b).

Additionally, the ability to clean syngas before it is combusted to produce electricity decreases air pollutants from gasification and makes emission control less complex and costly. Incinerators have no intermediate gas clean up; air pollution control occurs on exhaust gases only (Arena, 2012). There is also less heavy metal volatilization in gasification systems since the feedstock is not combusted (Engineering-Center for Environmental Research and Technology, 2009). Compared to incinerators, gasification produces over 100 times less dioxin and 10 times less mercury and nitrogen oxides (Young, 2010a).

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[17] The term waste-to-energy typically refers to an incineration process.

Table 4. Comparison of different gasification systems to incineration. Adapted from: (Arena, 2012; Lamers et al., 2013; Young, 2010a; Youngs, 2011)

| Features | Incineration | Pyrolysis | Conventional Gasification | Plasma Arc Gasification |
|---|---|---|---|---|
| **Operating Temperature** | 850°C – 1,200°C | 500°C - 800°C | 550°C - 1600°C | 4,000°C - 7,000°C |
| **Stoichiometric ratio of oxygen** | >1 | 0 | <1 | <1 |
| **Atmosphere** | Air | Inert/nitrogen | Gasification agent: $O_2$, $H_2O$ | Gasification agent: $O_2$, $H_2O$ Plasma gas: $O_2$, $N_2$, Ar |
| **Pressure** | 1 bar | 1 bar | 1-45 bar | 1 bar |
| **Common Feedstock** | Mixed MSW, high level of feedstock flexibility | Biomass and MSW, low level of flexibility | MSW, RDF, sludge, medical waste, medium level of feedstock flexibility | MSW and RDF, sludge, medical waste, hazardous waste, high level of feedstock flexibility |
| **Produced Gases** | $CO_2$, $H_2O$, $O_2$, $N_2$, NOx, SOx, HCl, VOCs | CO, $H_2$, $CH_4$, and other hydrocarbons, $N_2$* | CO, $H_2$, $CO_2$,$H_2O$, $CH_4$, $N_2$* | CO, $H_2$, $CO_2$, $N_2$* |
| **Solid Phase** | ash | ash, coke (biochar) | slag, ash | vitrified slag, ash |
| **Liquid Phase** | none | Pyrolysis oil and water | none | none |
| **Gas Cleaning** | Air pollution controls implemented for flue gases at stack | Intermediate cleaning before gas utilization, difficulty removing tars | Intermediate cleaning before gas utilization | Higher levels of gas cleaning achieved by high temps of plasma arc |
| **Net Energy Efficiency** | Low-medium electrical efficiency; high thermal efficiency | Medium electrical efficiency; low thermal efficiency; potential source of liquid fuels | Higher electrical efficiency; low thermal efficiency; potential source of liquid fuels | High electrical efficiency; low thermal efficiency; potential source of liquid fuels; possibly high parasitic loads |
| **RPS Eligibility** | Not eligible in California | Possibly eligible in California | Possibly eligible in California | Possibly eligible in California |
| **Market Prevalence** | Most common form of energy recovery from solid waste worldwide | Currently 25 facilities operating worldwide, the majority located in Japan; capacity of <1.1 mil tons/yr | Available in commercial scale, still rare in U.S.; around 100 facilities world-wide; capacity of ~2.5 mil tons/yr | 15 facilities world-wide, several pilot scale operations in Europe and North America; capacity of ~0.3 mil tons/yr |

*The opportunity to clean syngas prior to combustion processes can prevent creation of NOx and SOx when combusting syngas.

These technologies also differ in feedstock compatibility. Incineration is capable of accepting the entire waste stream without pre-processing. Whereas, gasification can be limited in the materials it accepts and feedstocks typically requires some pre-processing. Specific feedstock limitations will vary across gasifier types. Higher levels of preprocessing increases costs but has the trade off of reduced maintenance requirements (Klein, 2002).

Gasification, like incineration, achieves high levels of volumetric reduction of the original feedstock, however the slag produced from high temperature gasification is non-leaching and can be used as an aggregate for cement and other building materials. Byproducts of incineration have to be disposed of in a specially designed landfilled to prevent leaching of the toxins and heavy metals found in incinerator ash (Choy et al., 2004).

Gasification systems also have 65% less output of exhaust per ton of processed feedstock, which can reduce the cost of pollution control systems (Murphy & McKeogh, 2004). This reduction in output gases occurs because for mass burn systems, air is injected into the combustion chamber to increase combustion levels. Additionally, burning a low molecular weight syngas is much cleaner than combustion of waste directly (Youngs, 2011). Combined with higher energy conversion efficiency, gasification generates electricity with fewer GHG emissions and criteria pollutants per unit electricity than incineration (Murphy & McKeogh, 2004).

Gasifier capacities range from three to 100 tpd. Systems are arranged in parallel to process higher feedstock throughputs, but with the drawback of higher operational costs. This modular configuration gives gasification more flexibility for use at smaller feedstock capacities, the ability to be installed in stages, and typically occupy less space than mass burn facilities (Murphy & McKeogh, 2004). Conversely, incineration is most economical for large scale operations and typically a combustion chamber is installed at the required capacity (Psomopoulous et al., 2009).

### 3.3. Gasification in California

A list compiled by the University of California, Riverside in 2009 reports 107 facilities operating thermal conversion technologies in 14 different countries processing waste materials. Of these gasification systems, the majority are processing MSW alone, and one quarter co-process MSW with industrial wastes, medical and biohazardous wastes, or municipal sludges (Engineering-Center for Environmental Research and Technology, 2009). Figure 8 provides a summary of system characteristics of gasification facilities worldwide. Only four gasification operations are located in the U.S. processing MSW.

Gasification is the mostly widely adopted technology, but pyrolysis was also utilized early on. From 1990 to 1999, 16 gasification and pyrolysis facilities were installed worldwide, with an average processing capacity of 140 tpd (Lamers et al., 2013). From 2000 to 2009, 88 facilities were installed, with an increased average processing capacity of 160 tpd (Engineering-Center for Environmental Research and Technology, 2009). The first plasma-assisted gasification systems started becoming commercially available in 2002 at capacities of 25 tpd. As of 2003, syngas from gasification was being used to produce Fischer-Tropsch liquids, a ethanol-equivalent fuel (Engineering-Center for Environmental Research and Technology, 2009; U.S. DOE National Energy Technology Laboratory, 2010). In the U.S. since 2010, three plasma arc assisted gasification systems have been planned for installation.

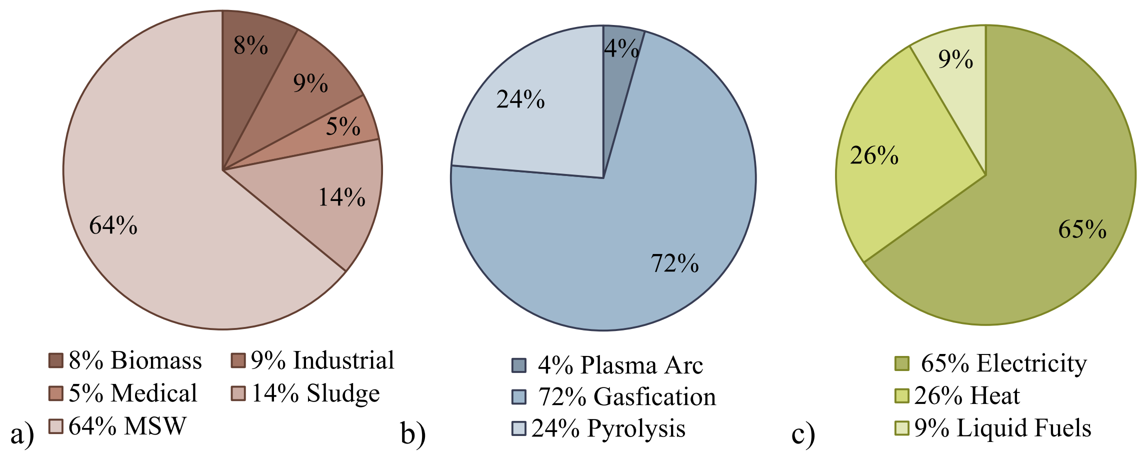


Figure 8. Proportions of (a) feedstocks, (b) technology, and (c) syngas utilization of thermal conversion facilities worldwide. Data source: (U.S. DOE National Energy Technology Laboratory, 2010)

In a status report from October 2008, eight cities and counties in California[18] were in different stages of acquiring thermal conversion technologies including gasification, pyrolysis, and plasma arc gasification. This no longer includes the City of

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[18] These included Los Angeles County and City of Los Angeles, City and County of Santa Barbara, City of Sacramento, San Jose, Salinas Valley, Santa Cruz County, City of San Diego, and Orange County.

Sacramento, who has halted a plasma arc gasification project they were pursuing for two years. They have determined this project to be unfeasible due to concerns that the project would not be eligible as a source of renewable energy, which would affect the economic viability of the system (Venn, 2009).

In 2009, the City and County of Santa Barbara issued a Request for Proposals and released a report with a short list of technologies that included five gasification technologies: AdaptiveARC,[19] International Environmental Solutions, Interstate Waste Technologies, Plasco Energy Group, and Tajiguas Partners with Entech (Alternative Resources, Inc., 2008b).

In response to a 2005 conversion technology evaluation report, the County of Los Angeles authorized the development of three conversion technology demonstration sites in 2010. Participants in these demonstrations included Arrow Ecology and Engineering, with an anaerobic digestion technology, International Environmental Solutions, with a pyrolysis technology, and NTech Environmental with a low temperature gasification technology. Los Angeles intends to develop a larger commercial scale facility depending on the outcomes of the demonstrations (Predpall et al., 2005).

The Salinas Valley Solid Waste Authority has entered negotiations with two venders: Urbaser S.A., with an AD technology, and Plasco Energy, with plasma arc gasification. In 2010, CalReycle delivered a legal opinion on gasification, which gave

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[19] At this time AdaptiveARC went under the company name of AdaptiveNRG.

Plasco pre-certification from the California Energy Commission, as a renewable energy source for the plant in Salinas Valley. In 2011, Plasco was awarded the contract for a facility located on the local landfill (Plasco Energy Group, 2012). In May of 2012, the facility's pre-approval as a renewable energy source was reverse by CalReycle Director Carrol Mortensen. This decision was attributed to definitions in the regulations that are vague and subject to interpretation.[20] After this decision, Plasco unsuccessfully lobbied for an exception to the new definition. In the end, the plant was officially put on hold in November of 2012 because it would no longer be an economic investment without renewable eligibility (Rubin, 2012).

Most recently, Sierra Energy was awarded two grants to construct gasification facilities in Sacramento and Monterey County. They were first awarded a $5 million grant in August of 2012 from the California Energy Commissions to build a commercial demonstration facility, which would produce biofuels from syngas at the Port of West Sacramento. In November of 2012, Sierra Energy was awarded a $3 million grant by the Depart of Defense to install a similar gasification system on the U.S. Army Garrison Fort Hunter Liggett in Monterey County which would service the community (Turner, 2012).

[20] See APPENDIX A: for the definition provided in AB32.

### 3.4. Market Available Gasification Systems

A list of market available gasification systems was derived from the reports released by Santa Barbra in 2008 and Los Angeles in 2005, in which they review available waste conversion technologies. Five companies were identified as potential technology providers for Humboldt County: AdaptiveARC, Entech Renewable Energy Systems, International Environmental Solutions (IES), Instate Waste Technologies (IWT), and Plasco Energy Group. These are all companies that met screening parameters including: scale, 20 year technology operational time, waste suitability, production of marketable byproducts, compliance with environmental standards in California, and credible suppliers (not debarred from contracting) in California (Alternative Resources, Inc., 2008b; Predpall et al., 2005). A complete list of evaluation criteria is available in Appendix B.

A request for information (RFI) was sent to each of these companies with details of the local waste stream from the Humboldt County Waste Characterization Study. The full RFI is available in Appendix C. The next sections provide a brief overview of each of these companies and the gasification technology they are producing.

#### 3.4.1 AdaptiveARC

AdaptiveARC is based out of Oceanside, California. They produce a portable and modular patented cool plasma gasification system to process MSW. Plasma is generated from electricity and high-pressure air. The plasma field reaches 1,260°C to 1,815°C to produce syngas from either unsorted or sorted waste. A diesel combustion engine is used to produce electricity from syngas. Solid by-products include commercial salt and char. The car is converted to an ash that can be repurposed as a construction aggregate. The system also produces potable water (Alternative Resources, Inc., 2008b). A diagram of the system is shown in Figure 9.

Their longest operating AdaptiveARC demonstration facility is a 100 ton per day (tpd) pilot plant installed in Monterey, Mexico that has operated daily to process MSW since 2005. The unit has also been used to process mined landfilled waste (Alternative Resources, Inc., 2008b).

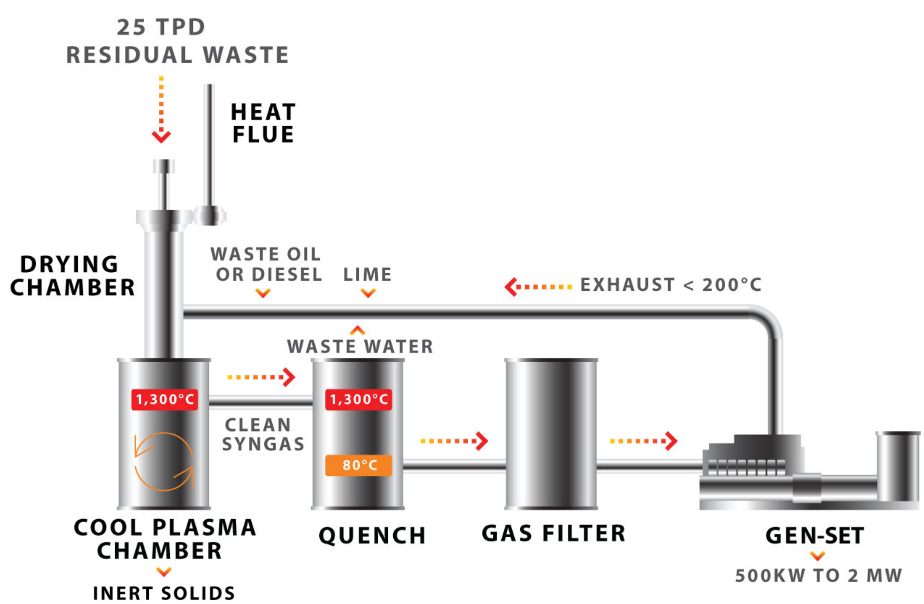


Figure 9. Flow diagram of AdaptiveARC's plasma arc gasification system. This is diagram shows a single gasifier unit providing syngas to a generator set. The inert solids leave the cool plasma chamber in the form of fly ash at 5% the weight of the incoming residual. Image source: (AdaptiveARC, 2012)

### 3.4.2 Entech Renewable Energy Solutions

Entech Renewable Energy Solutions operates out of two main offices in Pickering, Canada and Canning Vale, Australia. Entech produces a patented low temperature-substiochiometric gasification system that uses a fixed bed reactor to process biomass, medical, hazardous, and municipal solid wastes. Feedstock is heated in a low oxygen environment to approximately 815°C to form syngas that is combusted in a heat recovery boiler for steam and electrical generation. A diagram of this system is shown in Figure 10.

Their oldest operating gasification system is a 67 tpd commercial facility operating in Genting, Malaysia since 1998. Entech has over 100 commercial installations that process over 4 million tons of waste annually (Entech-Renewable Energy Solutions Pty Ltd, 2012).

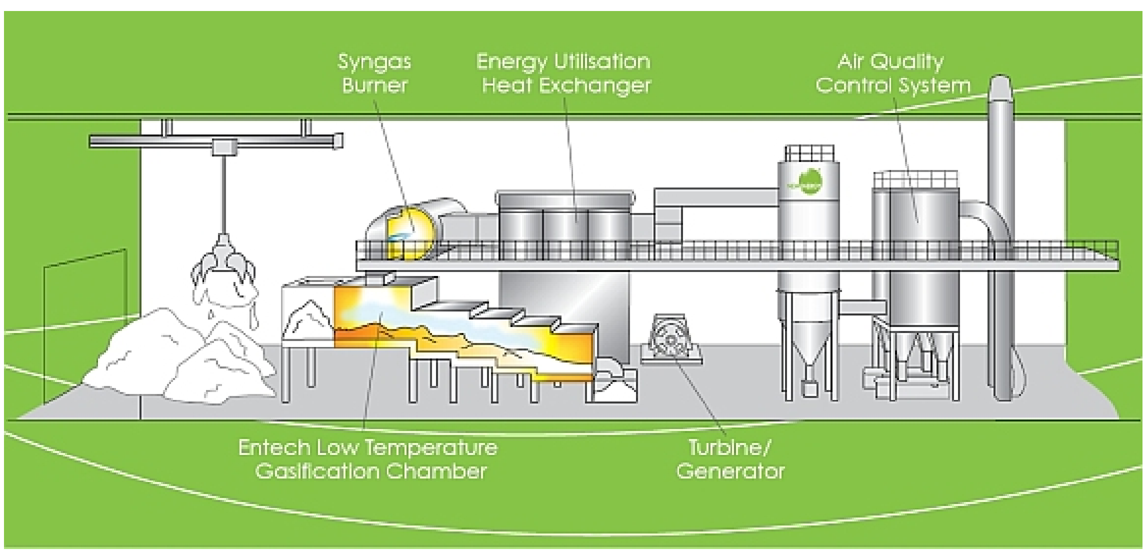


Figure 10. Flow diagram of Entech's low temperature gasification system. Entech offers modular gasifier units at the scale of 5 to 100 tpd. Image source: (Gomez et al., 2013)

### 3.4.3 International Environmental Solutions

International Environmental Solutions is a company based out of Romoland, California. IES produces a thermal pyrolysis technology they call the "IES Advanced Pyrolytic System". The system has several capacity configurations ranging from eight to 100 tpd. This system heats a dried and shredded feedstock in an 815 °C environment with limited oxygen to produce syngas. The syngas is used as heat source for a Rankine cycle system to produce electricity. Recyclable metals and glass are also recovered at the back end of this system, as well as char that can possibly be repurposed as a building material. IES is also researching the possibility of producing hydrogen. A diagram of the system is shown in Figure 11.

IES has a 50 tpd pilot plant located in Romoland, California. The plant has operated intermittently since 2004 and has been used for testing and processing various feedstocks including over 6,000 tons of post-MRF MSW (Alternative Resources, Inc., 2008b).

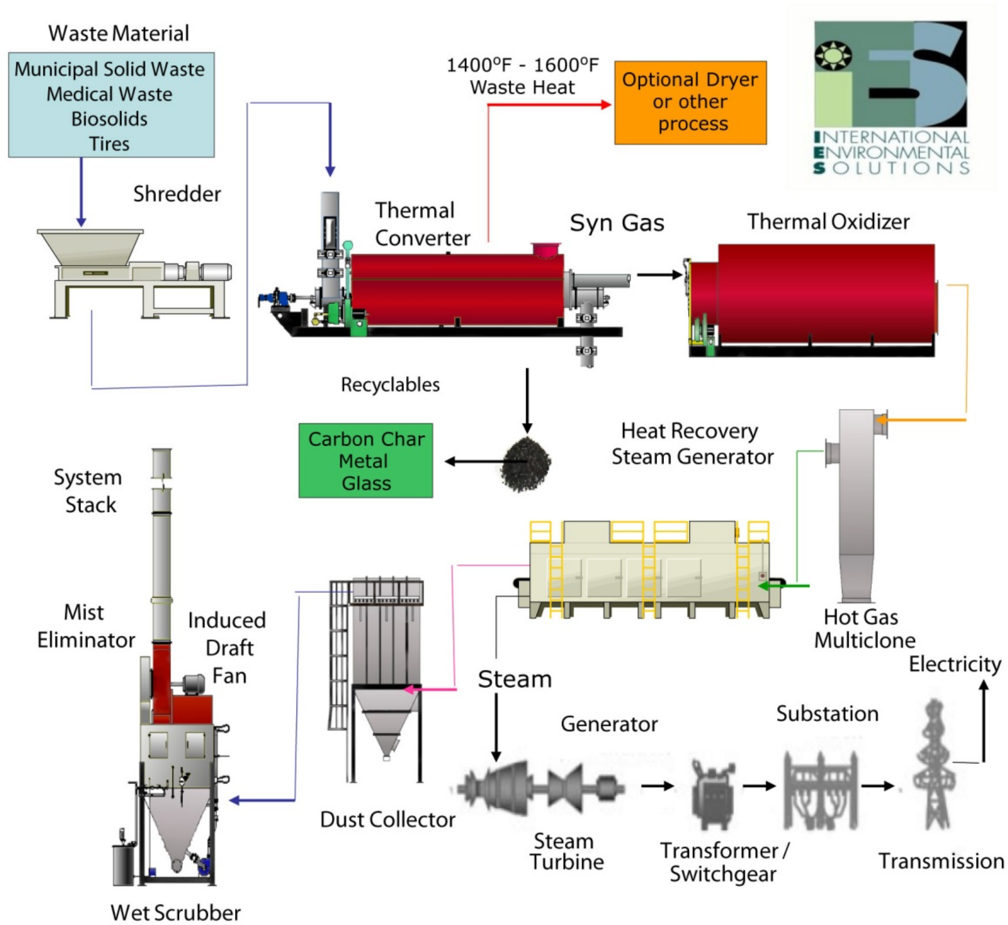


Figure 11. Flow diagram of International Environmental Solution's Advanced Pyrolytic System. This system utilizes syngas as a heat source for a Rankine cycle to produce electricity. Image source: (Alternative Resources, Inc., 2007)

### 3.4.4 Interstate Waste Technologies

Interstate Waste Technologies (IWT) is a company out of Malvern, Pennsylvania. IWT has a patented "Thermoselect" process that they describe as a closed loop, high-temperature gasification system. This system compacts feedstock into "plugs". This waste is then transferred into a reactor where temperatures as high as 1,000°C converts waste into syngas and carbon char. The char is further processed in a 2,000°C, oxygen enriched chamber to again produce syngas as well as a glassy slag. The process also recovers metals. Syngas that has been cooled and cleaned is used to generate electricity in a combined cycle gas turbine (Interstate Waste Technologies, 2007). A diagram of this system is shown in Figure 12.

IWT currently has commercial operations in seven locations in Japan. Their oldest operating facility is a 330 tpd plant, installed in 1999 in Chiba. Their largest facility, which has been operational in Kurashiki since 2005, processes approximately 190,000 tpd of MSW, industrial waste, and incinerator ash (Alternative Resources, Inc., 2008b).

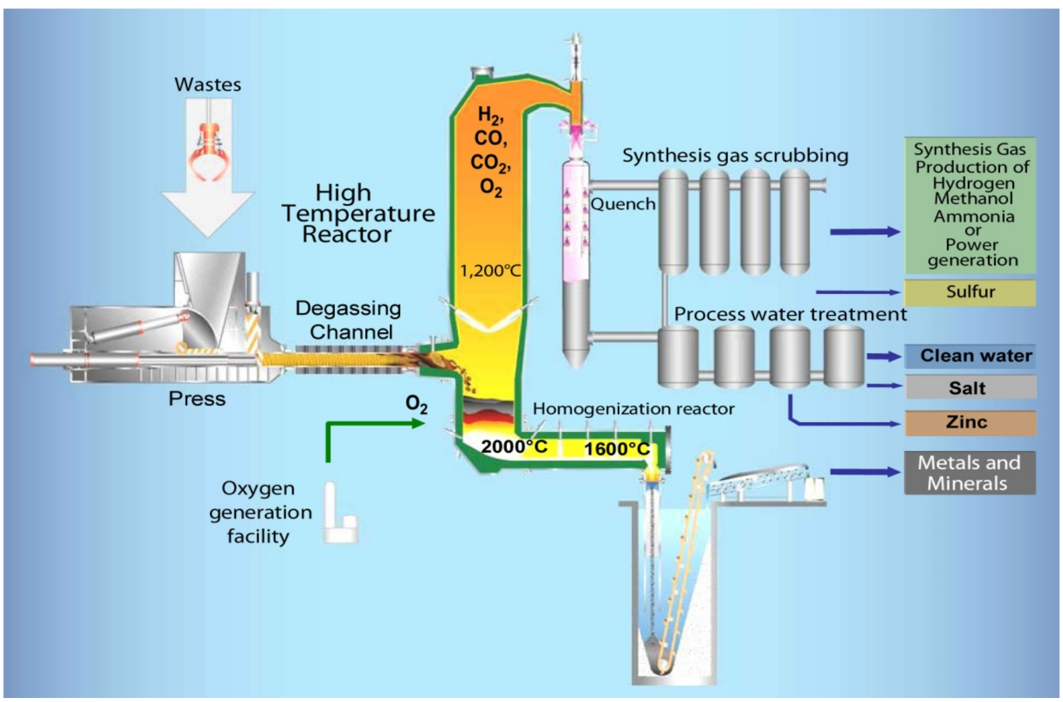


Figure 12. Flow diagram of Interstate Waste Technology's Closed Loop High Temperature Gasification System. The IWT System compacts waste feedstock as a part of pre-processing for gasification. Image source: (Lamers et al., 2013)

### 3.4.5 Plasco Energy Group

Plasco Energy Group, based out of Ottawa, Canada, produces a high temperature hybrid gasification-plasma arc system that uses a patented process they call the “Plasco Conversion System”. After preprocessing, which includes shredding and metal recovery, waste is gasified in a converter chamber to produce syngas. A secondary chamber refines the crude syngas with plasma torches. The syngas is cleaned a second time before combusted in Jenbacher gas engines to generate electricity (Alternative Resources, Inc., 2008b). The other byproducts of this system are solids that can be used as a construction aggregate, and potable water (Plasco Energy Group, 2012). See Figure 14 for a diagram of the Plasco system.

Plasco has been operating a 110 tpd commercial scale demonstration facility in Ottawa, Canada since 2007. This facility processed MSW and to improve system performance the Plasco system adds a supplemental waste stream made up of high-energy content materials, such as tires. Plasco also has a 5.5 tpd facility in Castellgali, Spain which has been in operation since 2003 (Plasco Energy Group, 2012).

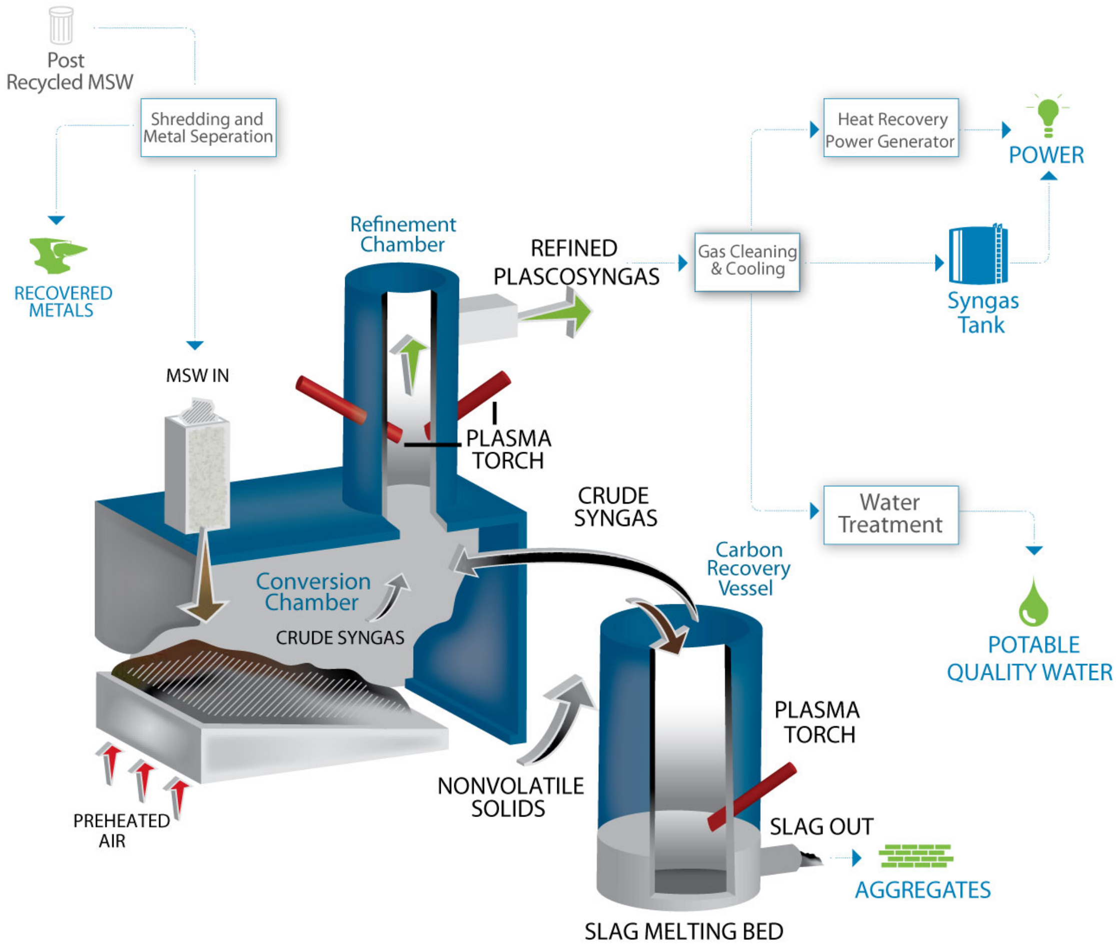


Figure 13. Flow diagram of the Plasco Conversion System. Plasco produces a hybrid gasification system that uses a gasification chamber and then plasma torches for syngas refinement. Image source: (Plasco Energy Group, 2012)

# CHAPTER 4. HUMBOLDT WASTE MANAGEMENT AUTHORITY

This chapter summarizes current management practices of the Humboldt Waste Management Authority (HWMA), a Joint Powers Authority formed in 1999 by Member Agencies of the incorporated cities of Arcata, Blue Lake, Eureka, Ferndale, Rio Dell, and the County of Humboldt. HWMA provides waste management services for the Member Agencies. Serving the majority of the county, HWMA is governed by a Board of Directors, composed of elected officials appointed by each Member Agency. HWMA oversees waste disposal services as well as waste management planning and tracks generation and disposal data. Recent efforts include a partnership on a Countywide Waste Characterization Study, creating a Strategic Plan for the next ten years, and the implementation of a food waste diversion pilot program. HWMA is also in the permitting stage of a local anaerobic digester project that will produce electricity from biogas (Humboldt Waste Management Authority, 2013a).

Integrated waste management services offered by HWMA include collection of household hazardous waste, universal waste and electronic waste, drop-off for mixed and source-separated recycling, a recycling buy back center, and operation of a green waste composting facility. A diagram of HWMA's integrated waste management system is shown in Figure 14. These programs have assisted Humboldt County in meeting waste diversion goals laid out in AB 939, though some areas of Humboldt County have not yet met 50% diversion (Test, 2012). Even with these diversion services, the majority of HWMA's operations and revenues are sourced mainly from solid waste disposal. The next sections cover HWMA operations in more detail and outline some of the challenges faced by the organization.

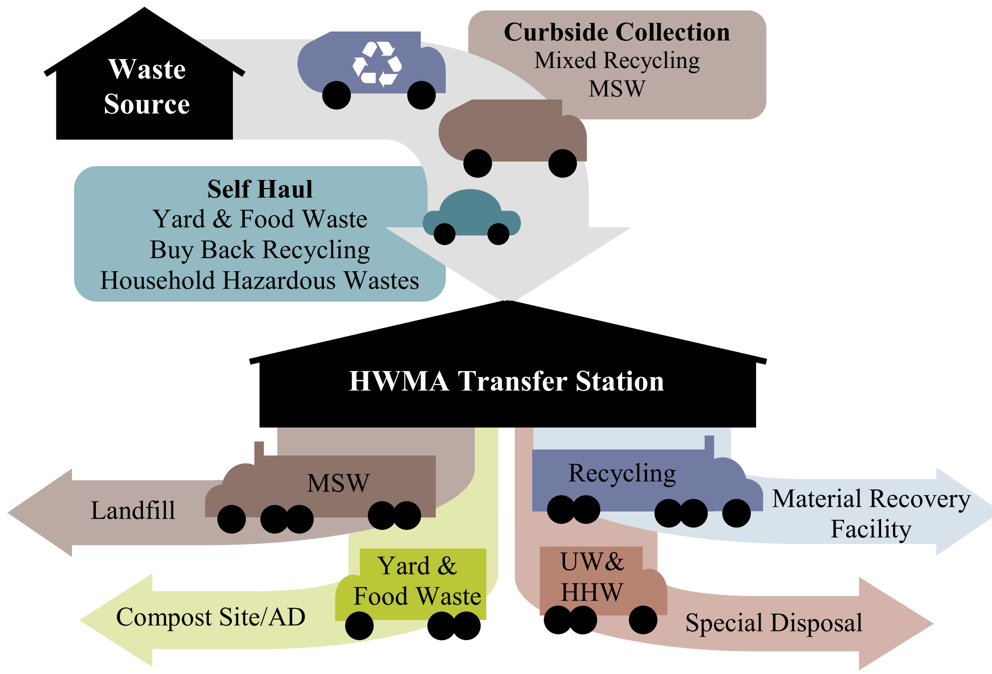


Figure 14. Flow diagram illustrating management of municipal solid waste by HWMA.[21] Waste is collection through franchised curbside collection or self-hauled by residential and commercial entities. From the transfer station, waste streams are sent to processing facilities for disposal. Yard wastes go to a local composting facility. Source separated food waste is currently sent to an external composting site, but in the future will be processed in a local anaerobic digester (AD). In the case of universal and household hazardous waste (UW & HHW), this could be several unique processing sites depending on the material.

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[21] Information about the Humboldt County waste processing by HWMA was provided by interviews with HWMA staff and HWMA publications including their website.

## 4.1. HWMA Programs

HWMA owns and oversees the closure of Cummings Road Landfill, which was open from 1935 until June of 2000.[22] This landfill is sited on 36 acres outside the City of Eureka, and contains 1,825,212 tons of waste (Oquendo, 2013). State law requires HWMA to oversee the post-closure maintenance and monitoring of the landfill for at least thirty years.[23] Currently an energy recovery system is not in place and collected landfill gas is flared at a rate of 200 standard cubic feet per minute (Humboldt Waste Management Authority, 2010).

The main HWMA operations occur at the Hawthorn Street Transfer Station in Eureka. Because there is no longer an operational local landfill, HWMA contracts with two out of county landfill sites. Approximately 40% of the total tonnage goes to Dry Creek landfill in White City, Oregon, and 60% is sent to Anderson Landfill, in Anderson, California (Bohn, 2010).[24] Municipal solid waste is loaded into trailers at the Transfer Station then hauled in possum belly chip trailers through a long-term contract with Bettendorf Trucking (Test, 2012).[25]

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[22] The Cummings Road Landfill was opened before many of the regulations for sanitary landfills and pollution control were put in place.

[23] This is a regulatory requirement is subject to approval, and could extend beyond 30 years (Duffy, Owen, Bohn, & Chavez, 2012).

[24] The redundancy of contracting with two landfills serves to provide a backup option in case one of the few roads coming in out of the county becomes impassible (Bohn, 2010).

[25] Each of these trailer can hold approximately 21 tons of waste (Bohn, 2010).

The majority of MSW is delivered to the transfer station by franchise haulers, private companies that provide curbside collection service. There are six hauling operations in the county. Most offer curbside recycling pickup inside city limits. Curbside green waste pickup is only available with the franchise service in Eureka. The Hawthorn Street Transfer Station also accepts self-hauled waste. There is a weigh house on site and self-haul customers are charged by the ton. There is a minimum fee for self-hauled waste up to 160 tons (Humboldt Waste Management Authority, 2013a).

In the last five years, HWMA's annual tonnage has decreased by more than 20%. MSW processed by HWMA decreased from 86,216 tons in the 2007 fiscal year to 66,987 tons in the 2012 fiscal year (Sherman, 2012).[26] Figure 15 shows historical MSW tonnages processed through HWMA.

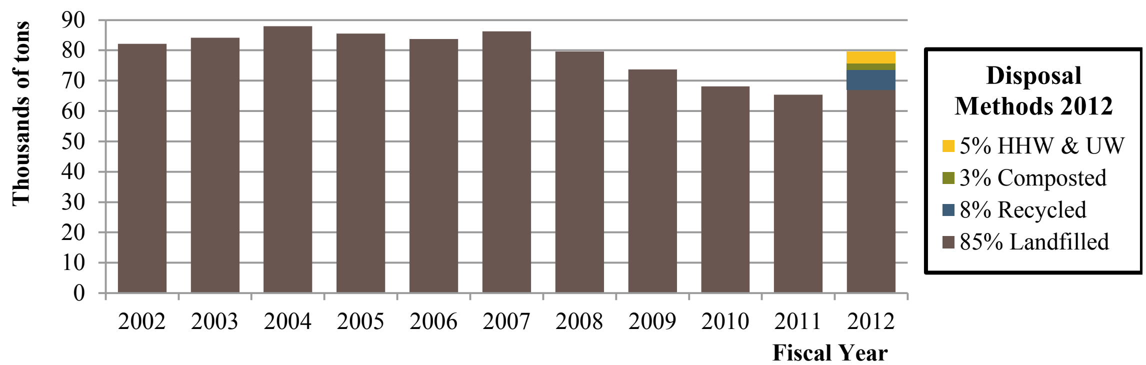


Figure 15. Past HWMA waste throughputs with diversion tonnages for 2012. MSW tonnages shown are for the last 10 fiscal years. Diversion data is only presented for the 2012 fiscal year. Source: (Sherman, 2012)

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[26] The HWMA fiscal year extends from July 1$^{st}$ through June 30$^{th}$. For example, the 2007 fiscal year would take place from July 1, 2006 through June 30, 2007.

The HWMA Hawthorne Facility also has a business office, a California Redemption Value (CRV)[27] buyback center and recycling drop off, a permanent household hazardous waste collection facility, and a green waste collection site. Seven to twenty tons of recycling per month come in through the buyback program. This separated recyclable material is baled and stored on site. Once enough bales are collected to fill a truck, they are transported to Sacramento, California. In 2011, a five-year contract was signed with Solid Waste of Willits in Willits, California to process comingled recycling, starting in September of 2011. HWMA now receives approximately 550 tons of mixed recycling each month (Egerer, 2012a).[28] Pictures of the transfer station are shown in Figure 16.

The permanent household hazardous waste (HHW) collection facility collects both wet and dry household hazardous waste including paint, batteries, electronic devices, and light bulbs. Some of these materials are recycled, some destroyed and some sent to specialized landfills, all at facilities that are far away. Flammable fluids like used motor oil are sent to Washington state as a feedstock for a kiln in a cement factory. HWMA has a grant to transport used tires to Lehigh, CA where they are shredded to make tire derived aggregate. Disposal of sharps, pharmaceuticals, and medical wastes is carried out through a contract with Stericycle. Fertilizers, household

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[27] CRV a is refund that is offered by the state for recycling certain beverage containers.

[28] The amount of recycling reported here does not account for all the recycling in the county only the recycling that is collected by HWMA.

cleaners and other toxic wastes are collected in 55-gallon drums and stored at the transfer station until enough accumulate for a shipment (Whitener, 2012).

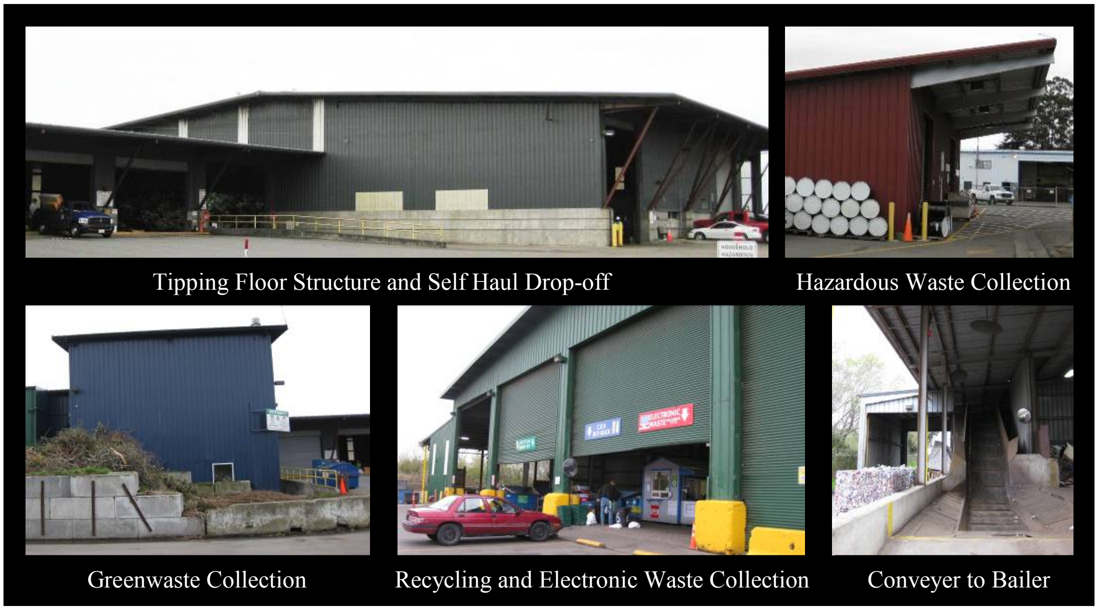


Figure 16. Images of HWMA operations out of the Hawthorn Street Transfer Station.

Yard wastes are collected along with untreated wood. The majority of this greenwaste is sent to HWMA's Mad River Compost Facility on West End Road in northern Arcata. This site does not accept food waste, dirt, sod, or treated wood. About 15% of the greenwaste is used as fuel in local biomass facilities for electricity generation (Humboldt Waste Management Authority, 2012a).

HWMA is currently in the planning stage of installing an anaerobic biodigester in southern Eureka. The digester will process source separated pre and post-consumer food waste from commercial and residential generators to produce electricity, heat and compost. There are only two digesters processing post-consumer food waste in California, but 15 others are in various stages of development (Bohn, 2010). This project will cost an estimated $5 to $7 million dollars to implement. Once implemented, the project will reduce waste management costs by $12 to $16 million dollars over 20 years. The digester is to be sited next to the Elk River Waste Water Treatment Plant on Hilfiker Road. Early adopters are already diverting food waste as part of a food waste collection pilot. The pilot is funded by a grant from the Environmental Protection Agency, for its potential to mitigate GHG emissions. During the interim, the collected food waste is sent to Cold Creek Compost in Ukiah, California, the nearest permitted food waste composting facility (Scott-Goforth, 2012).

### 4.2. Rate Structure

The majority of HWMA's revenues are generated through solid waste tipping fees charged to users of the disposal system. The HWMA projects costs to set a levelized disposal fee each year, also referred to as a tipping fee. In 2012, 24% of HWMA's MSW was self-hauled, 11% came from satellite facilities like Eel River Disposal, and 65% from franchise haulers. HWMA has different tipping fees for these three waste sources, but receives an average of $126.75 per ton MSW. This rate is significantly higher than the national average of $42 per ton (Arsova, van Harren, Goldstein, Kaufman, & Themelis, 2008).

The tipping fee covers the cost of MSW disposal but also finances many other HWMA operations and programs. Figure 17 (a) shows the allocation of tipping fee revenues to HWMA operations. Almost half of this fee is dedicated to hauling and the landfill disposal fees. The actual cost of hauling MSW will vary from week to week depending on fuel prices. A portion of the tipping fee is unallocated and used to cover variation in transportation costs. The disposal fee is set by the contract with each landfill. The contract with Anderson Landfill will be renewed in 2014, and the contract with Cold Creek in 2015. HWMA expects that these rates will be increased, possibly to $30 from the current $20.70 per ton (Duffy et al., 2012).

Another third of HWMA's MSW tipping fee covers operation expenses, and the rest funds programs such as the maintenance of the Cummings Road Landfill and household hazardous waste collection events (Humboldt Waste Management Authority, 2011).[29] A sample allocation of the tipping fee from one ton of MSW is shown in Figure 17 (b).[30]

Curbside collection rates are determined and charged by the individual franchise haulers. Each franchise has their own rate structure that is like a monthly subscription for waste services. Within this structure, households and businesses pay higher rates depending on their container volume, such as 20 gallons compared to a cubic yard (City of Arcata, 2012).

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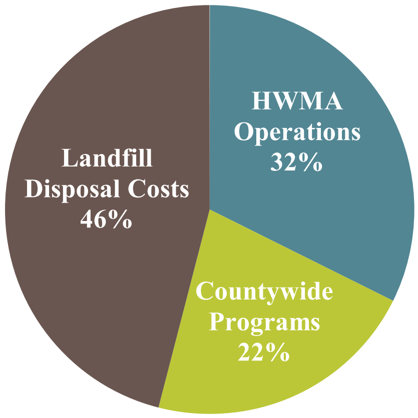
[29] There are currently 37 staff members employed by HWMA in positions of management, finance, scale operation, transfer station operation, household hazardous waste processing, recycling, and landfill maintenance(Humboldt Waste Management Authority, 2012b).

[30] Wood chips are frequently transported as a backhaul from the landfill and reduce the cost of waste transportation (Egerer, 2012c).

a)




b)

| FRANCHISE DISPOSAL FEE | |
|---|---|
| **Line Item** | **Cost per Ton** |
| Operations | $35.98 |
| Countywide Programs | $19.23 |
| Hauling to Landfill | $35.68 |
| Disposal Fee at Landfill | $24.67 |
| Unallocated Portion | $6.26 |
| **Average Disposal Fee** | **$123.31** |

Figure 17. HWMA disposal fees allocation for the 2012 FY. a) HWMA projected revenue allocations for the 2012 FY. b) Breakdown of the 2012 FY franchise tipping fee. The tipping fee is adjusted once each year, but costs, especially for hauling, can change frequently (Egerer, 2012c).

HWMA has differential tipping fees for diversion materials. Green waste is accepted at the Hawthorn facility for $90 per ton. HWMA charges the same $90 tipping fee for source separated food waste. This covers the cost of pre-processing performed by HWMA to reduce contamination, transportation to the composting facility, and the $23 per ton tipping fee charged by Cold Creek Compost (Egerer, 2012c).

Most common recyclable materials and appliances without freon can be dropped off free.[31] Under contract, Solid Waste of Willits pays for transportation of mixed recycling. Additionally, HWMA is paid $11.00 per ton of materials, including $3.00 for handling, with an additional dividend based on market prices (Egerer, 2012c). Other

[31] These include #1 - #7 plastic containers, glass, metals, cardboard, mixed paper, magazines, chipboard, and soft-cover books. Fluorescent tubes, compact fluorescent lights, used oil and oil filters, HID lights are also free for non-commercial disposal (Humboldt Waste Management Authority, 2013a).

bulk recycling materials that HWMA collects are rigid plastics, corrugated cardboard, and scrap metal, which can be sold for \$85 to \$185 per ton. The Recycling Center also offers a buyback service for CRV materials. Refunds will range from \$0.105 per pound for glass to \$1.59 per pound of aluminum. There is a fee charged for disposal of items that are more difficult to recycle, including refrigerators, electronic waste, televisions, and hard-bound books (Humboldt Waste Management Authority, 2013a).

There are different disposal rates for commercial or residential sources of HHW and these rates can also differ by material. For example, households can dispose of up to 10 fluorescent bulbs for free and are charged five dollars for up to 15 gallons or 125 pounds of HHW. HWMA makes HHW disposal pricing available to the public on their website. Excluding tire disposal, these programs cost HWMA over \$300,000 a year, mostly in transportation expenses (Whitener, 2012).

### 4.3. Waste Management Challenges for HWMA

The geographic isolation of Humboldt County requires long distance hauling to dispose or recycle waste. Solid waste is hauled a weighted average of 184 miles for landfill disposal. Recycling travels 133 miles for sorting and subsequently may travel as far as China for processing (The Economist, 2007).[32] Source separated food waste currently travels 155 miles to Ukiah; however, this is an interim location while a local

[32] The majority of paper reprocessing is done in factories in China (The Economist, 2007).

anaerobic digestion facility is developed. Hazardous waste materials can travel even further. Flammable hazardous liquids are transported to Western Washington, fluorescent lamps go to southern California for recycling, wet cell batteries go to Alabama to have the lead recovered, and medical wastes go to Utah to be incinerated (Whitener, 2012). The high cost of hauling from Humboldt County makes it challenging to divert uncommonly recycled materials, like plastic bags, even if the community is willing to separate them (Egerer, 2012a).[33] There is also a high environmental cost associated with waste disposal and diversion, since waste and diversion are transported by diesel truck from the county.

A growing concern at HWMA is the long-term viability of the current rate structure. This disposal rate structure was designed before there were state incentives for diversion and at a time when the Cummings Landfill was still accepting waste (Test, 2012). Implementing diversion programs and technologies requires additional staff and funding. Most revenues come from solid waste tip fees, which could conceivably serve as a disincentive for diversion, however escalating and volatile fuel prices continue to increase costs and risk to HWMA.[34] HWMA's tip fees are set annually and cannot

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[33] Plastic bags are one of the more costly materials to recycle. They are fluffy which makes hauling inefficient and as a lower quality plastic often cannot be sold at rate that covers transport out of Humboldt County.

[34] In 2008 when diesel when from $3.50 a gallon in February to $5.00 in May and did not return to $3.50 until October. This cost jump may have been balanced by the deflating waste tonnage happening at the time (U.S. Energy Information Administration, 2012a).

fluctuate freely as the price of diesel changes, and a large portion of the tip fee covers transportation costs. Therefore, there is a high level of risk associated with long distance transportation cost and fluctuating fuel prices.

The goal of 75% landfill diversion by 2020 mandated by AB 341 will exacerbate HWMA's problematic financial dependence on MSW disposal. Historically, waste diversion programs were subsidized through landfilled waste disposal fees. As the portion of diverted waste increases, landfilled waste decreases reducing the funding available for these programs. Increased waste diversion can reduce the need to pay high landfill disposal fees, but to achieve higher diversion rates requires investment of financial resources. This negative feedback loop is what the staff at HWMA refer to as the 'death spiral' (Test, 2012)

HWMA is also challenged by lack of flow control of some diversion material streams and by its inability to pass ordinances. Flow control is the authority to determine the destination of MSW processing, treatment or disposal within a jurisdiction. The contracts for franchise hauling are negotiated by each Member Agency. These constraints can make implementing new waste management practices difficult (Whitener, 2012).[35]

[35] San Luis Obispo County Integrated Wasted Management Authority has flow control and the authority to pass ordinances written into their Joint Power Authority Language. They have been able to pass local legislation establishing mandatory recycling and policies for disposal of universal wastes like mercury thermostats, batteries, and fluorescent tubes.

In response to these challenges and stricter diversion policies HWMA is developing a new strategic plan for the next ten years. This plan is to be developed based on the following objectives provided in the Request for Proposals, issued by HWMA for a consultant to assist with this planning:

- anticipate future needs/problems from discard/waste/recycling volume and regulatory changes;
- promote the long-term financial sustainability of programs and services;
- promote aggressive landfill diversion/recycling regionally;
- promote regional integration of (consistent) programs (e.g., curbside recycling, commercial food waste collection) among the various Member Agencies' collection systems;
- eliminate or minimize the risks to the Authority;
- maximize environmental progress;
- promote local economic development;
- ensure regulatory and contractual compliance; and
- increase public education regarding solid waste reduction and diversion matters (Humboldt Waste Management Authority, 2012b).

This feasibility study is meant to serve as an exploratory document to compliment the HWMA strategic planning process. Humboldt's rural setting, relativity small waste throughput, and high disposal fees make the county a potentially suitable context for deployment of gasification technology.

# CHAPTER 5. INTEGRATED GASIFICATION MANAGEMENT SYSTEM FOR HUMBOLDT COUNTY

Incorporating gasification to process HWMA's residual solid waste could greatly reduce dependence on landfill disposal of MSW. Germany, Sweden, Belgium, Denmark and Holland have all achieved landfill diversion rates of greater than 80% through a combination of public education campaigns, extensive recycling programs, and thermal conversion of residual waste (Youngs, 2011).[36] High population densities and limited space for landfilling puts more pressure on European countries to invest in alternative waste disposal technologies (Jamasb & Nepal, 2010). In the U.S., land availability makes landfilling waste the most affordable disposal option for most communities, but that is starting to change in many large cities and some rural regions like Humboldt County.

Many considerations went into designing an integrated waste management system for Humboldt County. The alternative waste management scenarios are all assumed to be managed and owned by HWMA, and the analysis only takes into account impacts and costs of waste that is currently sent to the landfill. As such, the feasibility analysis performed assumes all other programs and operations at HWMA will remain the same.

[36] Adoption of energy recovery systems in Europe is also driven by higher rates paid for renewable energy (Giugliano et al., 2008).

Gasification should not be direct replacement for landfill disposal. Instead, gasification should be part of an integrated waste system as presented by the U.S. EPA's hierarchy of waste management practices. Several guiding parameters were used to identifying parts of this waste management system that will be referred to as an "integrated gasification management system" or (IGMS). The factors considered include:

- reduction of the environmental impact of MSW disposal;
- compatibility with current HWMA operations and material flows:
- support of waste reduction and diversion programs;
- affordability, and
- adherence with local and state policy.

It is increasingly apparent that using a single disposal method, namely landfill disposal, for the wide variety of materials found in MSW is unsustainable. One way to address this problem is to segregate MSW into multiple waste streams. This can be accomplished by incorporation of a solid waste material recovery facility, or dirty MRF, which separates MSW using mechanical and manual sorting.[37]

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[37] There are benefits of using manual sorting that outweigh the increase in operation costs. It is an effective way to removing bulky items and hazardous materials that may damage sorting equipment and provides flexibility to the facility to change or add new diversion streams in response to market prices for materials. Manual sorting downstream of automated equipment improves capture rates and decrease contamination levels (Atchison, 2012).

While the focus of this thesis is examining the technical options for waste management, this not intended to de-emphasize the social and behavioral waste diversion practices. A dirty MRF can greatly increase diversion rates, even in communities like Humboldt, where recycling is strongly supported. Source separation is limited by multiple constraints of accessibility, user knowledge of diversion, motivation, and human error. Even so, continued involvement of the community in waste management can result in waste conscious purchasing and consumption decisions that support waste reduction and diversion (Chang, Davila, Dyson, & Brown, 2005). In addition, source separation reduces the amount of MSW that needs processing, reducing the costs of operating the dirty MRF. For these reasons source separation is considered complementary to central separation and it is recommended that HWMA continue utilizing current curbside recycling and diversion systems already in place countywide.

For compatibility with current operations, the dirty MRF in this analysis isolates material streams that are already diverted by HWMA. Diversion streams were also selected balancing the objectives of higher diversion rates and costs of operation and maintenance. The identified diversion streams include HHW, universal and electronic wastes, organic waste, recycling, and when providing preprocessing for gasification, rocks and fines, leaving residual waste.

Universal and hazardous waste separated from MSW will be diverted to previously established disposal or recycling sites identified by the HHW program. Removing hazardous waste and universal wastes decreases the toxicity of the final RDF feedstock by removing materials containing heavy metals and other target pollutants. This decreases the scrubbing requirements and pollutant levels in syngas that is combusted to produce electricity.

The proposed system would divert the majority of recyclables as a single stream for several reasons. Primarily, the available space in the tip floor building limits the amount of sorting equipment that can be installed. This will reduce the capital and operational costs of the MRF, but produce a lower quality recycling stream. Additionally, there are already several mixed recycling MRFs in the area.

In this analysis, it is assumed that mixed recycling will be sent to the Solid Waste of Willits sorting facility, with which HWMA has a five-year contract. There are a few high revenue bulky recycling items that could be recovered at the front end of the dirty MRF. These include large pieces of scrap metals, rigid plastics, and corrugated cardboard. Removing these large items also protects mechanical sorting equipment downstream.

A dirty MRF would also capture organic waste for digestion or composting without additional collection routes. In this analysis, it is assumed that the local anaerobic digester has the capacity to process 10,000 tons per year. Food waste above this amount assumed to go to the Cold Creek composting facility in Ukiah.[38] Large

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[38] With the installation of a dirty MRF and anticipated increased capture of compostable waste, HWMA would most likely install more anaerobic digestion capacity. For this analysis, diversion to Cold Creek is assumed because information about extending the digester capacity is not readily available.

pieces of untreated wood waste, also collected at the front end of the dirty MRF to protect machinery, will continue to be diverted to the local green waste composting site.[39]

Any inert materials such as concrete and fines that are not recoverable may still need to be landfilled since they can damage gasification equipment. These materials do not decompose and therefore do not contribute to landfill gas production.

All of the other non-recoverables make up the "residual". This material is shredded, and many gasification technologies recommending a shred size of less than three inches. Shredding helps makes the residual more uniform in size and moisture content, which increases the gasification efficiency. For this study, this shredded residual is referred to a residual derived fuel or RDF.[40]

While many gasifiers have been designed to accept problematic inert materials, like glass and metals, recovering them on the front end can decrease maintenance costs. The removal of food waste and other biogenic wastes can also improve gasification efficiencies by decreasing the moisture content of fuel waste, since on average food waste contains 70% water by mass. These diversion measures also decrease the required gasification system capacity, which can reduce capital, operation and maintenance costs. While not gaining economy of scale, small gasification systems are more proven,

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[39] Woody biomass and textiles are problematic materials for aerobic digestion because of long residency time that can slow material processing.

[40] Processed MSW for thermal processing is referred to in the literature as refuse derived fuel or solid recovered fuel. These labels are somewhat ambiguous and can be apply to fuel that has undergone other forms of preprocessing include enrichment, drying, and pelletizing (Young, 2010a).

demonstrated, and have greater social benefits in terms of lower perceived negative health impacts and visual effects (Jamasb & Nepal, 2010).

While a dirty MRF will be a considerable financial investment, such a facility would greatly assist in achieving state mandated diversion goals of 75% under AB 341. A dirty MRF would also assist in meeting the requirements for California Renewable Portfolio Standards eligibility of electricity produced from gasification of solid waste. The Renewables Portfolio Standard Eligibility Commission Guidebook, requires that conversion facilities must “reduced, recycled, or composted solid waste to the maximum extent feasible” and have “diverted at least 30% of all solid waste” to be applicable for eligibility, both of which would be achieved with centralized sorting (California Energy Commission, 2012).

To most accurately compare the environmental and economic performance of incorporating centralized sorting facility and gasification into the local waste management system, information was sought from vendors about market available systems. The next two sections describe the responses to these requests for information.

## 5.1. Solid Waste Material Recovery Facility Responses to Request for Information

In the summer of 2012, a Request for Information (RFI) was sent to four companies: CP Manufacturing, Enterprise Baler Company, Machinex Technologies, and Sierra International. The objective of this request was to determine:

- whether a solid waste material recovery facility could be designed to divert targeted waste streams of household hazardous waste, universal and electronic waste, recycling, compostables, inerts, and residual;
- if the current tipping floor is a viable site for this facility;
- an estimate of capital and operational costs of a facility appropriate for this application.

A description of the diversion demands of the proposed facility and diagrams of the HWMA tip floor were included in the RFI, available in Appendix D. Predictions of MSW flows for this analysis are estimated from daily averages taken from the 2009 through the 2012 fiscal years.[41] To annually process the 68,500 tons of MSW would require a facility capacity of 255 tpd.

To accommodate variation in material flows, the MRF is sized for a five-day, eight-hour work week. This provides flexibility to accommodate higher material flows through extended hours of operation. The maximum and minimum daily tonnage range, estimated from the monthly tonnages from the last four years, is 319 to 217 tpd. There are minor fluctuations in waste generation throughout the year as seen in Figure 18Figure 18. The highest monthly throughput in the dataset was 7,336 tons in July of 2008 and lowest was 4,575 tons in February of 2011 (Sherman, 2012).

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[41] An average of only the last four years is used since HWMA does not expect to return to pre-recession tonnages because of changes in local industry and future diversion programs (Test, 2012).

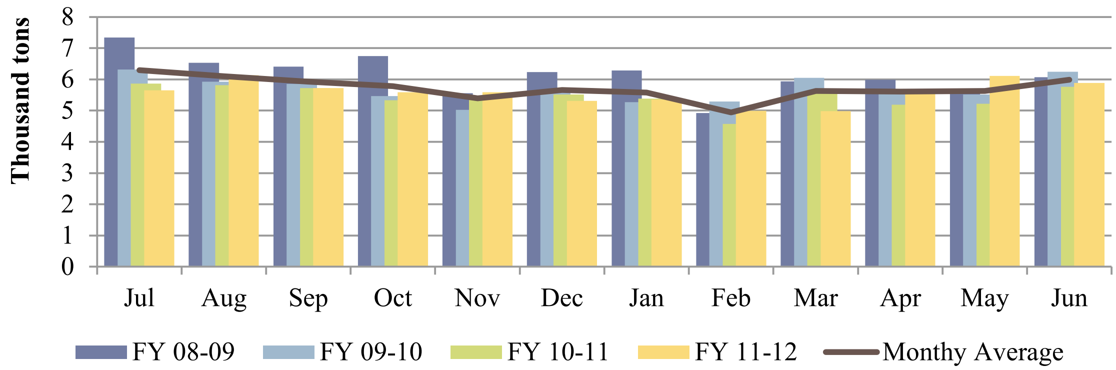


Figure 18. Monthly trends in HWMA material flows. Slight trends in waste throughputs are seen from the month to month tonnages. The high season seems to occur in the summer. Data source: (Sherman, 2012)

In addition to compatibility with these material flows, the request for information inquired about the possibility of installing a facility on the in the tipping floor at the Hawthorne Facility. Using this existing structure would eliminate the need for costly site development and would not require the restructuring of franchise collection systems. To accommodate the limited space on the tipping floor, diversion was limited to specific material streams.

Of the four companies, two complete responses were submitted by Sierra International and CP Manufacturing. Machinex Technologies Incorporated did not respond to the request. Enterprise Baler Co. declined to submit a quote because they stated they would be uncompetitive in a system that does not require a baler (Thomas, 2012). [42]

The response for Sierra International Machinery LLC came from the Recycling and Solid Waste Equipment division located in Keller, Texas, however Sierra's corporate headquarters is located in Bakersfield, California. Sierra International produces and sells equipment for scrap metal, recycling, RDF and solid waste industries. They also offer multiple services of system design, installation, equipment servicing, and operation and maintenance training to local staff when installing a system (Sierra International Machinery, LLC., 2012).

CP Manufacturing, Inc. is based in National City, CA. CP Manufacturing is a division of the CP group that includes Krause Manufacturing, MSS Optical Sorters, IPS Balers, and Advanced MRF. The CP Group has manufactured and installed over 400 material recovery facilities both nationally and internationally (CP Manufacturing, Inc., 2012). CP designs and install systems for solid waste, single stream recycling, preprocessing for waste to energy systems, construction and demolition recycling, and electronic waste recycling.

The responses from these companies were able to meet the objectives of this RFI. Both responses indicated that it would be possible to install a facility capable of sorting for the targeted waste streams in the existing tipping floor building (Atchison & CP

[42] HWMA already has a baler that they use to bundle sorted bulk recycling.

Group of Companies, 2012; Harris & Sierra International Machinery, 2012). To respect the confidentiality of these responses, specifics of a facility layout are omitted and representative costs for equipment, installation, and operations will be used in this analysis. This model assumes a 100% capture rate of each material category since is difficult to anticipate the precision of sorting which varies by material. Also, types of sorting equipment, facility layout, state of waste items, and degree of manual sorting all affect the capture rate (Kessler Consulting, Inc., 2009).

### 5.2. Gasification Systems Responses to Request for Information

Humboldt County would require a small-scale gasification system with a capacity of processing 80 tpd if operated 24 hours per day, seven days a week. This was calculated similarly to the MRF processing capacity, additionally taking into account error projected in the Characterization Study. The high and low throughputs are estimated to be 103 and 61 tpd. The five technology companies, described previously, were asked to provide information about their ability to meet the following criteria:

- appropriateness of scale for Humboldt County;
- environmental performance meeting California standards;
- compatibly with Humboldt County diversion goals; and
- ability to produce marketable byproducts.

In March of 2012, a Request for Information was sent to five companies. Three responses were submitted. There was no response from Interstate Waste Technologies or International Environmental Solutions.[43] Plasco Energy group declined to provide detailed information because the RDF throughput would not meet their minimum facility size of 330 tpd, equivalent to 120,450 tons a year. AdaptiveARC was able to submit a detailed response meeting all screening criteria. Entech Renewable Energy Solutions does produce and install small-scale gasifiers, but the information provided in their response to the RFI indicated that the Entech technology did not match the required scale for Humboldt County (Arca & Entech Renewable Energy Solutions, 2012). A summary of the Entech response is available in Appendix E. This left a single candidate, AdaptiveARC's cool plasma arc gasification system as a case study for this feasibility analysis. The following section contains and brief description of the AdaptiveARC technology and system configuration recommended for Humboldt County (Damore & AdaptiveARC, Inc., 2012).

For Humboldt County, AdaptiveARC recommends four "ce25" systems that process 27.5 tons each, for a total capacity of 110 tpd of RDF. The system uses two 3516 CAT 1.6 MW diesel engines, with two plasma gasification units supplying syngas

[43] IES was in correspondence before the request was submitted, but IES filed for bankruptcy early that month on March 13, 2012 ("Company Bankruptcy Information for International Environmental Solutions Corporation," 2012)

to a single generator to produce electricity.  Pictures of the ce25 system are shown in Figure 19.

The ce25 reactor chamber is top-loaded with feedstock from a drying column. This system uses a feedback loop of exhaust from the generators to heat the drying column and maintain a lower low level of oxygen in the reactor chamber.  The primary heat source for gasification is plasma torches powered by syngas.  In this process, the feedstock is first reduced to char which is further broken down into low-carbon fly ash. The resulting ash is 5% of the feedstock by weight and is marketable as an additive in cement.


Figure 19.  Images of AdaptiveARC's portable ce25.  Image source: (AdaptiveARC, 2012)

Syngas leaving the reactor passes through plasma fields for initial cleaning which breaks down organic and complex compounds. Water is used for cooling and cleaning syngas. After the temperature of syngas is decreased from 1,300°C to 80°C it is then passed through multiple filters to remove particulates and decrease acidity. The syngas is then cooled a second time with water to 20°C. No wastewater is produced by the system. Once water becomes unsuitable for cleaning the syngas, it is pumped back into the reactor where any pollutants are broken down.

The resulting syngas is combusted in stationary diesel Caterpillar engines. The syngas is mixed with ambient air and small amounts of diesel, which are injected with the syngas to support ignition. Energy density of the syngas will vary with the feedstock. In order to provide consistent electrical production, diesel input is automatically adjusted to provide make-up energy. At start up, each CAT 3516B LE engine requires 119 gallons per hour of diesel. After 20 to 25 minutes, the system will start to produce syngas that will decrease diesel demand to 6.8 gallons per hour. Some of the exhaust from the engines exits at the heat flue while the rest is directed back to heat the drying column and reactor.

This system is modular and portable. A ce25 can be transported on standard 18-wheeler 40' flat bed trailer and can be set up and operational within 32 hours. AdaptiveARC was able to provide information about their energy efficiency levels, capital and operational costs, and environmental performance for performing this analysis.

## 5.3. Descriptions of Alternative Management Systems

Based on information provided by the responses to the requests for information, this analysis will compare two alternative waste management systems to the continued landfilling of MSW. The first scenario uses a solid waste MRF for separating out divertible materials and then continues to use landfills for disposal, but only of residual waste. The second scenario also employs a solid waste MRF but additionally uses AdaptiveARC's cool plasma gasification system to process residual waste.

### 5.3.1 Continued Landfill Disposal

This scenario evaluated the continuation of the current MSW disposal system. This scenario will be referred to simply as *Landfill Disposal* or LFD. This scenario has HWMA continuing to send solid waste to the Anderson and Dry Creek Landfills with Bettendorf Trucking under HWMA's current contracts. Figure 20 show the material flow diagram with all MSW sent to landfills.

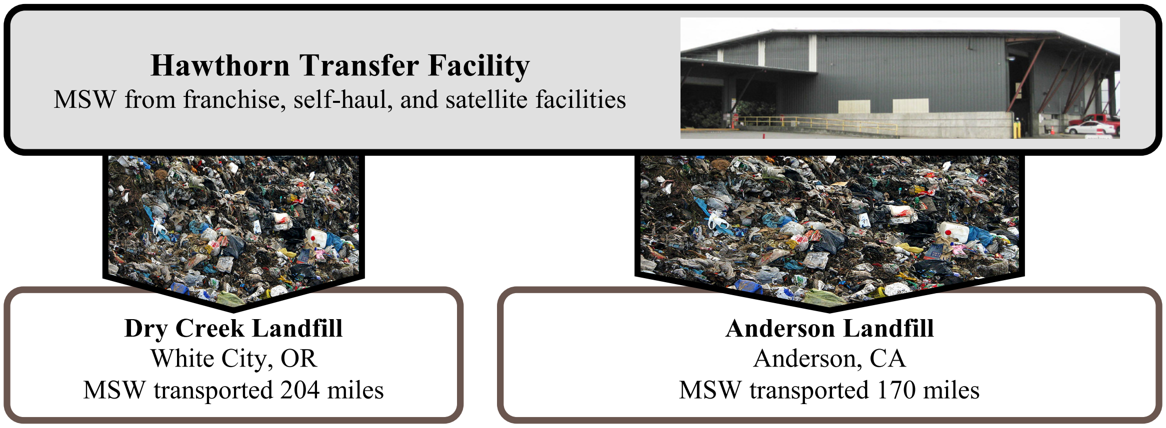


Figure 20. Material flows for continued landfill disposal of MSW. The majority of MSW is sent to Anderson Landfill (60%) and the remaining (40%) is sent to Dry Creek Landfill.

**5.3.2. Landfill Disposal of Only Residual Wastes**

In this scenario, all MSW is processed in a dirty MRF installed at the HWMA Transfer Station. The MRF will divert household hazardous wastes, universal wastes, and recoverable materials, which are processed accordingly. In this management system only residual is landfilled and will be referred to in this analysis as *Landfill Post-Material Recovery Facility* or LF P-MRF. As seen in Figure 21, hazardous and universal wastes are diverted to the programs already in place at HWMA, which allows these materials to be recycled or disposed of through pre-established channels.

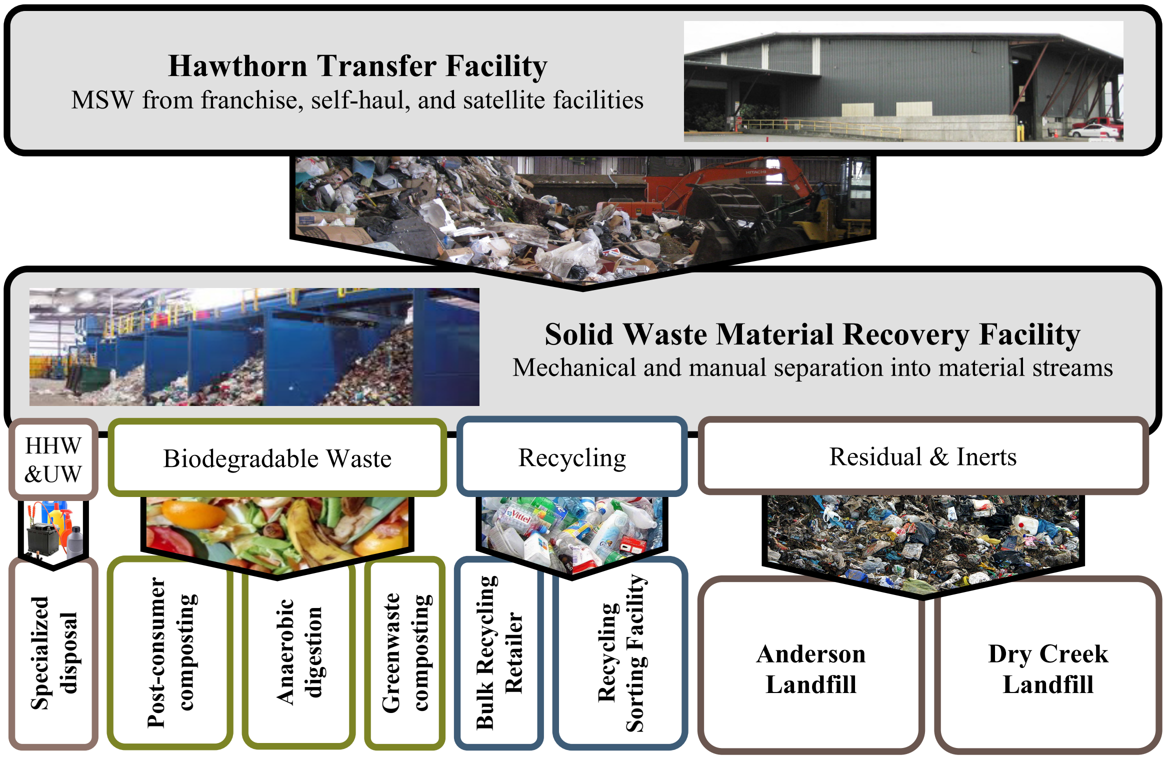


Figure 21. Material flows in an integrated management system landfilling post-MRF residual. This system requires the installation of a Solid Waste Material Recovery Facility to separate recoverable waste leaving only residual waste for landfill disposal.

Compostable waste will either be transported to the local green waste compost facility, processed by anaerobic digestion, or sent to the Cold Creek composting facility in Ukiah. In this analysis, it is assumed that HWMA has an operating 10,000 ton per year anaerobic digestion facility with a 350 kW electrical productive yield.

From the MRF, three bulk streams of recycling are recovered: corrugated cardboard, scrap metals, and rigid plastics. All other recycling is collected as a single stream for processing at the Solid Waste of Willits sorting facility. Finally, all remaining residual is landfilled under the current contracts with Anderson and Dry Creek Landfill.

### 5.3.3. Integrated Gasification Management System

The *Integrated Gasification Management System*, or IGMS, scenario uses the installation of a dirty MRF to divert hazardous and recoverable materials as in the previous scenario with the addition of a shredder for processing RDF. This scenario assumes a 110 tpd plasma arc gasification system by AdaptiveARC is installed at the HWMA Transfer Station.

The electricity produced from this system powers HWMA operations including the dirty MRF and the surplus electricity is sold to the grid. The same diversion streams are achieved by the MRF in the same volumes as in the previous management system with the addition of an inert stream, which is landfilled. Finally, fly ash from the gasifiers is sold to a cement company based in the Sacramento area. Figure 22 shows a material flow diagram of this scenario.

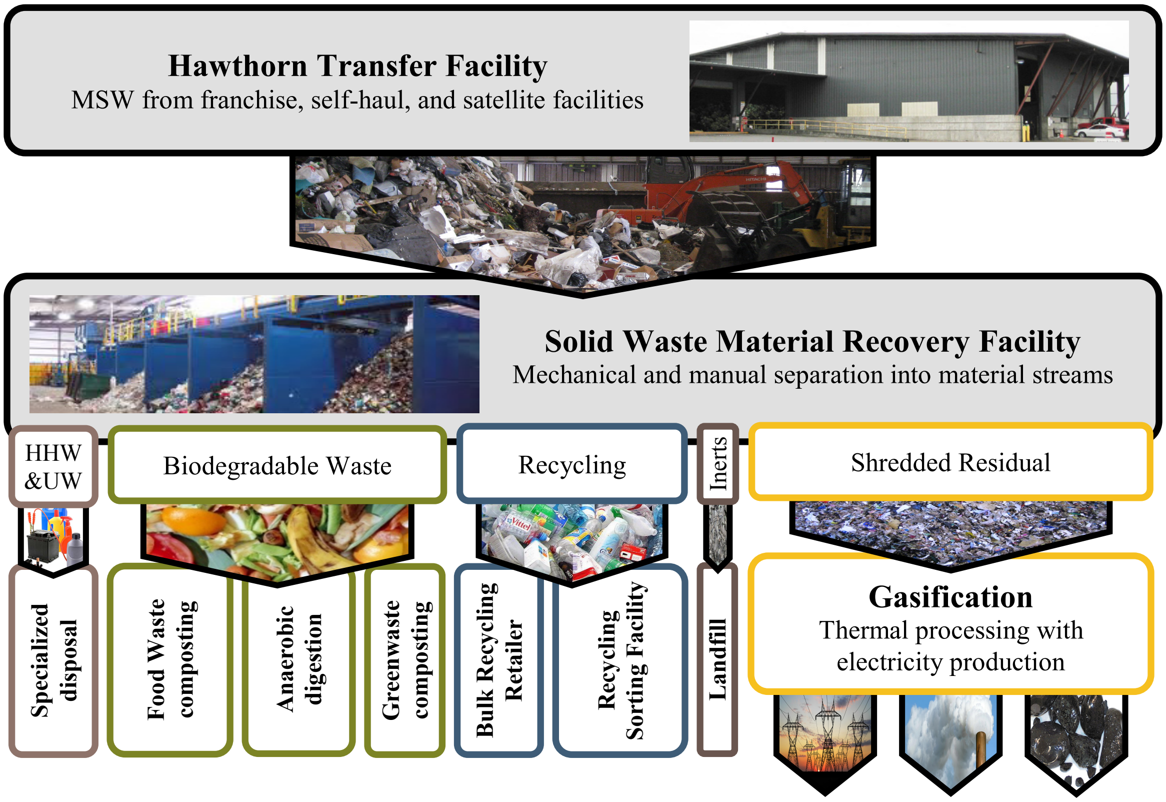


Figure 22. Material flows in IGMS with gasification of post-MRF residual. This system uses the proposed 110 tpd AdaptiveARC gasification system to locally processes this RDF. There is an additional step of shredding residual from the MRF. Byproducts of the gasification system include fly ash, as well as electricity and flue gases from syngas utilization.

Because of the uncertainty of renewable eligibility for electricity from gasification in California (discussed in section 3.3), three different pricing scenarios were investigated. The first pricing scenario classifies RDF as a non-renewable energy source, which is referred to as *IGMS (NR)*. The second scenario operates the same as IGMS (NR) but classifies all RDF as a renewable source and prorates the electricity produced by energy source to account for the addition of diesel fuel for co-firing and make-up (California Energy Commission, 2012). This designation is used in other hybrid renewable systems like concentrated solar collectors where natural gas is used to provide make-up heating in base load applications (Turchi, Langle, Bedilion, & Libby, 2011). This scenario with renewable electricity prorated is referred to as *IGMS (PR)* for this analysis. The third scenario uses biodiesel in place to petroleum diesel and classifies all the electricity produced as renewable energy. For this scenario, modifications are made to the torches and generator to accept 100% soy based biodiesel (B100) available from Renner in Humboldt County. This system is noted as *IGMS (BD)*.

In all there are five waste management systems modeled in this analysis: continued landfill disposal, sorting waste and landfilling only undivertible materials, and finally integrating gasification for disposal of residual with the three electricity pricing schemes. The next section describes the assumptions and methods used to build these models and the key factors compared in the feasibility analysis.

# CHAPTER 6. METHODS

This chapter describes the methods used in this analysis to assess the feasibility of incorporating advanced waste management technologies into HWMA's waste management system. In this study, feasibility is characterized as the ability to meet the following waste management goals:

- reduce the environmental impact of MSW disposal,
- provide affordable waste management for the Humboldt community, and
- support local and state initiatives for waste reduction and diversion.

To identify the most appropriate integrated waste management system, descriptive analysis tools were used to compare the alternative management systems described in the previous chapter. The sections that follow describe the methodology and assumptions used to perform a materials flow accounting, an assessment of greenhouse gas emissions, and lifecycle cost analysis for each of these systems (Finnveden, Björklund, Moberg, & Ekvall, 2007).

## 6.1. Material Flows and Diversion Potential

An estimate for future MSW throughputs was determined from HWMA historic flow data and information gathered from interviews. An average from fiscal years of 2009 through 2012 serves as a static annual tonnage for this analysis. Only the last four years of data are used since HWMA's tonnage projections do not have them returning to pre-2008 throughput levels.

Potential diversion streams and flow rates were identified and quantified from the Humboldt County Waste Characterization Report. Capacity requirements for the dirty MRF and gasification system were determined from a calculated daily tonnage determined from monthly throughput data from the 2009 to 2012 fiscal years. This capacity requirement for the systems assumed a five-day workweek for the MRF, operating over an eight hour day, and the gasification system operating 24 hour per day and seven days per week.

### 6.2. Evaluation of Market Ready Conversion Technologies

Companies with the capacity to design and sell equipment for solid waste material recovery were approached with a Request for Information, which is available in Appendix D. An estimate for installing and operating this system was created from the quotes provided.

Thermal conversion technologies contacted for this evaluation were selected from reviewing short listed companies from recent evaluation processes done by Santa Barbara in 2008 and Los Angeles in 2005. More information about these evaluations is available in Appendix B. Each of the companies selected received a Request for Information, available in Appendix C, to determine if their technology met the following criteria:

- appropriateness of scale for Humboldt County;
- environmental performance meeting California standards;
- compatibly with Humboldt County diversion goals; and

- ability to produce marketable byproducts.

The failure to meet any of these above listed screening criteria disqualified a company from the evaluation process. Only the AdaptiveARC system met these criteria, and as such, was selected as the gasification technology investigated in this analysis.

### 6.3. Energy Profile of RDF and Gasification System

The following equations were used determine an approximate energy content of Humboldt's RDF and electrical generation capacity for the gasification system selected for analysis. Average energy content of RDF was determined by compiling typical energy densities and moisture levels of each material according to the prevalence of each material in the local residual stream (Energy Information Administration, 2007; Kaplan et al., 2009; Tchobanoglous & Kreith, 2002).[44]

The following formulas were used to determine the energy, in million BTU (MMBtu), and moisture characteristics of Humboldt RDF :

[44] American sources of energy densities typically report the HHV and European sources more typically report the LHV. Following this trend, values used in this analysis are the HHV.

$$\text{Energy Density}\left(\frac{\text{MMBtu}}{\text{dry ton}}\right) = \sum\nolimits_{m} \rho_m \times n_m$$

$$\text{Overall Moisture Content (\%)} = \sum\nolimits_{m} w_m * n_m$$

$$\text{Energy Density}\left(\frac{\text{MMBtu}}{\text{wet ton}}\right) = \sum\nolimits_{m} [\rho_m \times n_m \times (1 - w_m)]$$

$\Sigma_m$ denotes the summation over all *m* materials
$\rho_m$ = energy density of each material in MMBtu/dry ton
$n_m$ = percentage of each material in RDF by mass
$w_m$ = typical moisture content of each material

To determine properties of composite materials, a standard heating value and moisture content of mixed MSW was determined by averaging values presented recently in the literature (since 2007). See Table 5. Composite materials were listed in the Characterization Study by a primary material (i.e. composite plastic or composite organic) and were assumed to contain 75% of a primary material and 25% mixed solid waste by mass.

Table 5. Typical heating values and moisture contents of mixed MSW and their sources. The value used in this study is an average of values reported since 2007.

| Energy density of mixed MSW (MMBtu/ton) | Moisture content of mixed MSW by percentage mass | Source |
|---|---|---|
| 9 | 20% | Tchobanoglous and Krieth, 2002 |
| 11.73 | -- | EIA, 2007 |
| 10.97 | 27% | Kaplan et al., 2009 |
| 11.32 | 21% | Young, 2010 |
| **11.34** | **24%** | Average assumption use for this study |

The net energy density in one short ton of RDF was determined by taking into account the total energy available in a wet ton of waste materials and the energy required to evaporate the moisture in the waste (Borganakke & Sibbtag, 2009). This value was multiplied by the gasifier efficiency and feed rate to determine the power provided by syngas in units of MMBtu per hour.

$$\text{Power from syngas (MMBtu/hr)} = (\rho_{RDF} - (w \times L)) \times f \times \eta_{gas}$$

w = average moisture content (%)
$\rho_{RDF}$ = average energy density (MMBtu/wet ton)
$\eta_{gas}$ = conversion efficiency of the gasifier (%)
L = latent heat of water vaporization, equivalent to 1.94 MMBtu/ton water
f = feed rate (tons/hr)

The power produced by the genset was determined by calculating the available energy from syngas and diesel fuels. Diesel is used to co-fire syngas in the generator and used to partially power the plasma torches. An alternative scenario uses 100% biodiesel in the AdaptiveARC system. The energy densities of these liquid fuels are provided by the United State Department of Energy (US DOE) and are listed in Table 6. The efficiency rating for the generator set was applied to the total available energy to estimate the potential gross power output of the system.

$$\text{Gross power yield (MW)} = (p_{syn} + p_{liq}) \times \eta_{gen} \times C$$

$p_{syn}$ = rate of energy from syngas (MMBtu/hr)
$p_{liq}$ = rate of energy from additional fuels (MMBtu/hr)
$\eta_{gen}$ = efficiency of generator (%)
C = conversion for MMBtu to MWh (0.293 MWh/MMBtu)

Table 6. Energy density of different fuels (U.S. Department of Energy, 2013)

| Fuel | Energy Density |
|---|---|
| Diesel | 0.14 MMBtu/gal |
| Biodiesel (B100) | 0.12 MMBtu/gal |
| Liquid Propane | 0.08 MMBtu/gal |

In this case, the energy available from syngas exceeds the demand of the generator. Therefore, the nameplate power rating of the generator was used to estimate the annual gross power yield of the system, along with the hours of operation determined from the annual throughput of residual. This calculation method does not take into account all the energy available from syngas, but provides compensation for the occasional lags in energy quality that occur with RDF as a feedstock. The productive yield of the gasification system takes into account parasitic loads of the gasifier and HWMA operations, including operation of the solid waste MRF.

$$\text{Annual productive electricity yield (MWh/yr)} = ((P \times \frac{T}{F} \times \eta_{tf}) \times (1-\eta_p)) - D_h - D_m$$

$P$ = gross power yield (MW)
$T$ = RDF (tons/year)
$F$ = feed rate (tons/hr)
$\eta_{tf}$ = transformer and transmission efficiency (%)
$\eta_p$ = parasitic demand of gasification system (%)
$D_h$ = HWMA operations annual electrical demand (MWh/yr)
$D_m$ = Dirty MRF annual electrical demand (MWh/yr)

The productive electrical yield of the anaerobic digestion system was determined from characteristics described in Bohn's 2010 analysis and HWMA's Food Waste to Watts Program description, summarized in Table 7.

Table 7. Profile of HWMA's aerobic digestion program (Bohn, 2010; Humboldt Waste Management Authority, 2013a)

| | |
|---|---|
| AD capacity | 10,000 tpy |
| Productive yield per ton | 0.25 MWh/ton |
| Annual productive yield | 2,500 MWh/yr |
| Levelized cost of operations | \$47.00/ton |

### 6.4. Greenhouse Gas Emissions Assessment

The environmental impact of the different waste management systems was quantified by performing an assessment of GHG emissions. This assessment inventoried Scope 1 and Scope 2 emissions as defined by the Intergovernmental Panel on Climate Change (IPCC) in metric tons of carbon dioxide equivalent ($tCO_2e$) over 20 years (Intergovernmental Panel on Climate Change, 2006).

The amount of methane emissions from landfilling of solid waste was calculated from an equation provided by the Climate Action Reserve (CAR) protocol that assumes the recovery rate of methane generated from landfilled waste is 75% from years four through 10, and 100% release of methane to the atmosphere during the first three years (Climate Action Reserve, 2011). The values are shown in Table 8, in units of metric ton of carbon dioxide equivalent ($tCO_2e$) emissions, are multiplied by the amount of biodegradable waste landfilled each year. This is the method HWMA uses to quantify the savings from their food waste diversion project (Bohn, 2010).

Table 8. GHG emissions produced by a landfilled ton of biodegradable waste over 10 years. This model is provided by CAR and assumes no landfill gas capture for the first 3 years and then 75% capture for the next 7 years. Figure adapted from (Bohn, 2010)

| **Year(s) in landfill** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **$tCO_2e$ emissions per wet ton waste** | 0.220 | 0.183 | 0.152 | 0.032 | 0.026 | 0.022 | 0.018 | 0.015 | 0.013 | 0.010 | **0.692** |

Emissions from long haul trucking of MSW, compost, and recycling were calculated with the following equation using emission factors from Table 9, assuming each trailer could carry 21 tons of materials:

$$\text{Annual transportation emissions } \left(\frac{MtCO_2e}{year}\right) = \frac{\text{miles traveled}}{\text{year}} \times \frac{\text{gallon diesel}}{mile} \times \frac{tCO_2e}{gallon\ diesel}$$

Table 9. Energy and carbon intensity of selected fuels (California Climate Action Registry, 2009)

| **Fuel** | **Carbon Intensity** |
|---|---|
| Diesel as a transport fuel | 10.15 kg $CO_2e$ /gallon |
| Biodiesel (B100) | 9.5 kg $CO_2e$ /gallon |
| Liquid propane | 5.74 kg $CO_2e$ /gallon |

The total GHG emissions for the landfill disposal (LFD) scenario served as the baseline for comparing the alternative management systems and was estimated using the following model:

$$\text{LFD emissions } (tCO_2e \text{ over 20 years}) = (N \times E_t) + E_{lfg}$$

N = periods (years)
$E_t$ = annual emissions from transportation ($tCO_2e$/yr)
$E_{lf}$ = 20 year emissions from landfill gas from decomposable portion of waste ($tCO_2e$)

The emission sources inventoried in the scenario where MSW is sorted by a MRF and only residual is landfilled (LF P-MRF) included the transportation of residual to the landfill and production of landfill gas, generation of electricity consumed by the dirty MRF, and transportation and processing of diversion streams. Emissions from biogenic wastes that are composted, digested, or gasified were assigned a Biogenic Accounting Factor (BAF) of zero, following an emissions accounting methodology from the Accounting Framework for Biogenic Carbon Dioxide Emissions from Stationary Sources released in 2011 by the U.S. EPA. Under this same framework, biofuels also have a BAF of zero (U.S. Environmental Protection Agency, 2011). The following equation summarizes the emissions from operating the LF P-MRF scenario over 20 years:

$$\text{LF P-MRF emissions } (tCO_2e \text{ over 20 years}) =$$

$$E_{lfg} + (N \times (E_t + (L \times E_{pe}) + (BAF \times T_{AD} \times E_{AD}) + (BAF \times T_C \times E_C)]$$

$N$ = periods (years)
$L$ = electrical consumption (MWh/yr)
$T_{AD}$ = tons of waste digested (tons/year)
$T_C$ = tons of waste composted (tons/year)
BAF = Biogenic Accounting Factor

$E_t$ = annual emissions from transportation ($tCO_2e$/yr)
$E_{lf}$ = 20 year emissions from landfill gas from decomposable portion of waste ($tCO_2e$)
$E_{pe}$ = emissions from purchased electricity ($tCO_2e$/MWh)
$E_{AD}$ = carbon intensity of anaerobic digestion ($tCO_2e$/ton)
$E_C$ = carbon intensity of open air composting ($tCO_2e$/ton)

AdaptiveARC provided target pollutant emission levels from gasification, but did not provide measured carbon dioxide emissions from combustion of syngas. These emissions are highly variable and depend on feedstock content, elevation, and other combustion conditions. No values were available in the literature, therefore an estimate of these emissions was made from the carbon balance of syngas combustion. The proportional mass of carbon in syngas produced from plasma gasification, is presented in a study by Lupa (Lupa et al., 2013). This chemical equation summarizes the combustion of syngas, taking into account only the carbon balance and the additional oxygen (outlined with a box) needed to achieve complete combustion.

$$60\ CO + 27\ CO_2 + 1\ CH_4 + \boxed{32\ O_2} \rightarrow 2\ H_2O + 88\ CO_2$$

The volume faction of carbon dioxide after combustion was multiplied by the atomic mass of carbon dioxide. The resulting mass of carbon dioxide was divided by the accumulative atomic mass of syngas. This proportion was applied to the mass of a dry ton of feedstock, minus the weight of remaining solids, to provide an estimate of carbon emissions per ton of residual derived fuel.

$$\text{Carbon intensity of RDF } \left(\frac{tCO_2e}{dry\ ton\ RDF}\right) =$$

$$(1\ dry\ ton\ RDF - 0.5\ tons\ solids) * \frac{mass\ of\ exahust\ CO_2}{mass\ of\ syngas +\ additional\ oxygen}$$

Using this value, the carbon intensity of electricity produced by the AdaptiveARC system was calculated using the following equation:

$$\text{Carbon intensity of electricity from gasification system } \left(\frac{tCO_2e}{MWh}\right) =$$

$$\frac{(T_{dRDF} \times E_{dRDF}) + (G_d \times E_d)}{L_g}$$

$T_{dRDF}$ = RDF (dry tons/year) $E_{dRDF}$ = carbon intensity of RDF ($tCO_2e$/dry ton)
$G_d$ = diesel fuel (gallons/year) $E_d$ = carbon intensity of diesel fuel ($tCO_2e$/gallon)

This equation was used to determine the percentage RDF that is biogenic:

$$\text{Biogenic portion per dry ton RDF (\%)} = \frac{\sum_b [n_b \times (1 - w_b)]}{n_{RDF} \times (1 - w_{RDF})}$$

$\Sigma_b$ denotes the summation over all *b* biogenic materials
$n_b$ = mass of each biogenic material in a wet ton of RDF by mass (tons)
$w_b$ = typical moisture content of each biogenic material (%)
$n_{RDF}$ = one ton of RDF by mass (tons)
$w_{RDF}$ = typical moisture content RDF (%)

The following additions are made to the previous equation to apply the BAF for emissions produced from biogenic fraction of RDF.

$$\text{Non-biogenic carbon intensity of electricity from syngas } \left(\frac{MtCO_2e}{MWh}\right) =$$

$$\frac{\left(((P_b \times BAF) + (1 - P_b)) \times T_{dRDF} \times E_{dRDF}\right) + (G_d \times E_d)}{L_g}$$

$P_b$ = Biogenic portion of RDF (% per dry ton)
BAF = Biogenic Accounting Factor
$T_{dRDF}$ = RDF (dry tons/year)
$E_{dRDF}$ = carbon intensity of RDF ($tCO_2e$/dry ton)
$G_d$ = diesel fuel (gallons/year)
$E_d$ = carbon intensity of diesel fuel ($tCO_2e$/gallon)
$L_g$ = annual gross electrical yield (MWh/year)

When operating the generator with biodiesel, the BAF applies also to the fuel portion of the equation, shown in this equation:

$$\text{Non-biogenic carbon intensity of electricity from syngas co-fired with biodiesel } \left(\frac{MtCO_2e}{MWh}\right) =$$

$$\frac{\left(((P_b \times BAF) + (1 - P_b)) \times T_{dRDF} \times E_{dRDF}\right) + (G_{bd} \times E_{bd} \times BAF)}{L_g}$$

$T_{dRDF}$ = Dry tons RDF per year
$P_b$ = biogenic portion of RDF (% per dry ton)
BAF = Biogenic Accounting Factor
$G_{bd}$ = biodiesel fuel (gallons/year)
$E_{dRDF}$ = carbon intensity of RDF ($tCO_2e$/dry ton)
$E_d$ = carbon intensity of biodiesel fuel ($tCO_2e$/gallon)

The emissions produced from an IGMS were determined from the following equation taking into account the annual emissions from the gasification system depending on the fuel co-fired with syngas:

$$\text{IGMS emissions (tCO}_2\text{e over 20 years)} =$$

$$(N \times (E_t + (L_g \times E_g) + (G_p \times E_P) + (BAF \times T_{AD} \times E_{AD}) + (BAF \times T_C \times E_C))$$

$N$ = periods (years)
$L_g$ = electricity generated from gasification system (MWh/yr)
$G_p$ = propane (gallons/year)
$T_{AD}$ = tons of waste digested (tons/year)
$T_C$ = tons of waste composted (tons/year)
BAF = Biogenic Accounting Factor
$E_t$ = annual emissions from transportation ($tCO_2e$/yr)
$E_g$ = non-biogenic emissions from gasification system ($tCO_2e$/MWh)
$E_P$ = carbon intensity of propane ($tCO_2e$/gallon)
$E_{AD}$ = carbon intensity of anaerobic digestion ($tCO_2e$/ton)
$E_C$ = carbon intensity of open air composting ($tCO_2e$/ton)

The carbon intensity of electricity produced by the Humboldt Bay Generating Station (HBGS) was estimated from generation and fuel consumption data available from the California Energy Commission's Energy Almanac. The average energy content of natural gas in California and the carbon emissions produced from 100% combustion of natural gas and distillate fuel oil, provided by U.S. Energy Information Administration (U.S. Energy Information Administration, 2011, 2013a). The Almanac provided records of annual energy consumption of natural gas and distillate fuel oil, in MMBtu per year, and the net electricity generation by each of the Station's engines (Pacific Gas and Electric Company & The California Energy Commission, 2013). The 2010 and 2011 carbon intensities for electricity from the Station was determined from the following equation and averaged:

$$\text{Carbon intensity of electricity from HBGS } \left(\frac{tCO_2e}{MWh}\right) = \frac{(P_{ng} \times E_{ng}) + (P_{dfo} \times E_{dfo})}{G}$$

$P_{ng}$ = average energy annually sourced from natural gas (MMBtu/ year)
$E_{ng}$ = carbon intensity of natural gas consumption ($tCO_2e$/MMBtu)
$P_{dfo}$ = average energy annually sourced from distillate fuel oil (MMBtu/ year)
$E_{dfo}$ = carbon intensity of distillate fuel oil consumption ($tCO_2e$/MMBtu)
G = annual net generation (MWh/year)

The potential avoided emissions from displacing electricity generation from the Humboldt Bay Generating Station with electricity produced by the aerobic digester and gasification systems was determined for each of the different scenarios using the following formula:

$$\text{Net emissions } (tCO_2e \text{ over 20 years}) = E_s - (N \times G_{net} \times E_h)$$

$E_s$ = emissions of management system (tCO2e)
N = periods (years)
$G_{net}$ = annual MWh of electricity sold to the grid
$E_h$ = carbon intensity of electricity produced from Humboldt Bay Generating Station ($tCO_2e$/MWh)

## 6.5. Lifecycle Cost Analysis

To compare the economic viability of the alternative management systems, the costs of implementing and operating each management scenario was estimated over a 20-year lifecycle. Several other metrics were used to compare these scenarios including a levelized cost of waste management in units of dollars per ton of MSW. In addition, a discounted payback period and internal rate of return on investment was determined for the alternative management systems by taking into account tipping fee revenues paid to HWMA. The formulas and key assumptions used to estimate these values are presented in the rest of this section.

A methodology from <u>The Solid Waste Handbook</u> by Robinson was used to determine the lifecycle cost (LCC) of each waste management system and is summarized in the following equation:

$$LLC\ (\$) = \sum_{n=0}^{20}\left[(C - R) \times \frac{(1+i)^n}{(1+d)^n}\right]$$

C = annual system cost (real $)
R = annual system revenue (real $)
i = inflation rate
d = discount rate
n = the period (years)

(Robinson, 1986)

The model constructed for this analysis used a net cash flow table and applied different rates of inflation to anticipate future prices of system consumables of diesel fuels, electricity, and water. The different inflation rates used in this analysis are listed in Table 10.

The General Inflation Rate was calculated from Customer Price Listings for urban customers from 1991 through 2011 provided by the U.S. Bureau of Labor Statistics (U.S. Department of Labor, Bureau of Labor Statistics, 2012). The general rate of inflation and inflation rates for consumables were determined using the following equation provided by a report released by the University of Central Florida:

$$Rate\ of\ inflation\ (\%) = \left[\left(\frac{C_o}{C_n}\right)^{\frac{1}{n}}\right] - 1$$

$C_o$ = current costs
$C_n$= baseline costs
n = periods from baseline (Raistad, 2010)

Both the diesel and electrical price escalation rates were determined from historic energy pricing dating from 1993 through 2013 provided by the U.S. Energy Information Administration (U.S. Energy Information Administration, 2012b). The escalation rate for water prices was determined from past and projected water rates provided by the City of Eureka for the 2010 to 2011 fiscal year through the 2014 to 2015 fiscal year (City of Eureka Finance Department, 2010).

Table 10. Inflation rates used in the economic analysis.

| | **Annual Rate** | **Data Source** |
|---|---|---|
| Discount Rate | 3.0% | (Rushing, Kneifel, & Lippiatt, 2011) |
| General Inflation Rate | 2.5% | (U.S. Department of Labor, Bureau of Labor Statistics, 2012) |
| Fuel Inflation Rate | 6.2% | (U.S. Energy Information Administration, 2012b) |
| Electricity Inflation Rate | 1.5 % | (U.S. Energy Information Administration, 2012b) |
| Water Inflation Rate | 7.7% | (City of Eureka Finance Department, 2010) |

A 3% real discount rate is recommended by the U.S. Department of Energy for renewable energy projects owned by federal facilities. This rate was used to determine the present value of future cash flows (Rushing et al., 2011).

The present day cost of consumables was determined from average historic prices. The present day cost of diesel was estimated from the average weekly cost of diesel over the 2012 fiscal year (U.S. Energy Information Administration, 2012b). The cost of biodiesel was determined from average prices of B100 in Eureka, California provided by Renner Petroleum (Galidy, 2012).

The present wholesale price for electricity was estimated from the average California Wholesale Market price per MWh in from March 2012 to 2013, available from the U.S. Energy Information Administration (U.S. Energy Information Administration, 2013b). The present day sale price of renewable electricity was based on Pacific Gas and Electric's average standard contracts prices for purchasing electricity from small producers (Pacific Gas and Electric Company, 2013a). The cost of purchase electricity was determined from the average rate paid by HWMA in from February 2011 through February 2012 (Jacobson, 2012).

Equipment costs for implementing the solid waste MRF and plasma arc gasification system were estimated from information provided by technology producer's RFI responses (Atchison & CP Group of Companies, 2012; Harris & Sierra International Machinery, 2012). The total implementation costs included equipment costs, installation costs, permitting and site development, and a 30% contingency.

The LCC analysis model for the landfill disposal scenario included the costs for hauling MSW and the landfill tipping fee, available in Appendix G, Table G.1. The model for LFD is summarized in the following formula using present values (PV):

$$\text{LFD LCC (\$)} = \sum_{n=0}^{20} \left[ \left( (C_t \times (1 + i_t)^n) + C_f \right) \times \left( \frac{1}{(1 + d)^n} \right) \right]$$

$C_t$ = PV annual cost of material transportation
$C_f$ = PV annual cost of contracted tipping fees
$i_t$ = fuel inflation rate
d = discount rate
n = period (years)

The LCC analysis model for LF P-MRF included the costs for implementing the MRF, operational costs for the facility, costs of transporting the separate waste streams, tipping fees, and revenues generated from recycling. A list of cost and revenue rates is available in Appendix G, Table G.1. The model for LF P-MRF is summarized in the following formula:

$$LF\ P-MRF\ LCC\ (\$) = (C_s \times e) + \sum_{n=0}^{20} \left[ \left( \frac{1}{(1+d)^n} \right) \times \begin{bmatrix} (C_{O\&M} \times (1+i)^n) + (C_e \times (1+i_e)^n) + (C_t \times (1+i_t)^n) + C_f + C_r \\ -\left( (R_b \times (1+i)^n) + R_m + R_s \right) \end{bmatrix} \right]$$

$C_s$ = PV cost of implementing system
e = contingency
$C_{O\&M}$ = PV annual cost of operations and maintenance
$C_e$ = PV annual cost of electricity
$C_t$ = PV annual cost of material transportation
$C_f$ = PV annual cost of contracted tipping fees
$C_r$ = PV annual cost of major equipment replacement
$R_b$ = PV annual revenue from bulk recycling
$R_m$ = PV annual contracted revenue from recycling
$R_s$ = PV equipment salvage revenue
i= general inflation rate
$i_t$ = fuel inflation rate
$i_e$ = electricity inflation rate
d = discount rate
n = period (years)

The LCC analysis model for IGMS included the costs for implementing a dirty MRF and AdaptiveARC 110 tpd plasma gasification system, operational costs for both facilities, costs of transporting the separate diversion streams, and material tipping fees.

Also included are revenues derived from recycling, electricity, and ash produced by gasification. The model for IGMS is summarized in the following formula:

$$\text{IGMS LCC (\$)} = (C_s \times e) +$$

$$\sum_{n=0}^{20}\left[\begin{bmatrix}(C_{O\&M} \times (1+i)^n) + (C_t \times (1+i_t)^n) + (C_w \times (1+i_w)^n) + (C_e \times (1+i_t)^n) + C_f + C_r \\ -\big((R_b \times (1+i)^n) + R_m + (R_e \times (1+i_e)^n) + (R_a \times (1+i)^n) + R_s\big)\end{bmatrix} \times \left(\frac{1}{(1+d)^n}\right)\right]$$

$C_s$ = PV cost of implementing systems
e = contingency
$C_{O\&M}$ = PV annual cost of operations and maintenance
$C_e$ = PV annual cost of diesel fuel
$C_w$ = PV annual cost of water
$C_t$ = PV annual cost of material transportation
$C_f$ = PV annual cost of contracted tipping fees
$C_r$ = PV annual cost of major equipment replacement
$R_b$ = PV annual bulk recycling revenue
$R_m$ = PV annual contracted recycling revenue
$R_e$ = PV annual electricity revenue
$R_a$ = PV annual ash revenue
$R_s$ = PV equipment salvage revenue
i= general inflation rate
$i_t$ = fuel inflation rate
$i_e$ = electricity inflation rate
d = discount rate
n = period (years)

Equipment replacement costs for the dirty MRF were estimated to be two percent of the initial capital cost and occur in years five, ten and fifteen. The operational costs were determined from recommended staffing requirements provided by companies using typical wages for Humboldt County (Glasmeirer, 2012). Current costs to HWMA were used for diverting recycling and composting. Materials for landfill disposal were priced assuming current disposal costs. Revenues from ash are set at zero, assuming the revenue will consistently cover the costs of transportation, and revenues from equipment salvage is also assumed to be zero. A list of cost and revenue rates is available in Appendix G, Table G.1.

A quantitative metric used to compare these systems developed for this analysis is a levelized cost of disposal (LCOD) in units of dollars per ton of processed MSW. The LCOD is a way to describe the fee per ton of waste HWMA would need to charge the community to recover costs of operating each management system. The LCOD was calculated using the following equation:

$$\text{LCOD (\$/ton)} = \frac{LCC}{\sum_n \frac{T_n}{(1+i)^n}}$$

LCC = discounted system lifecycle cost
$T_n$ = annual MSW processed (tons)
n = period of operation (year)
i = discount rate

To determine the net cash flow of each of the management systems, the revenue from the tipping fees charged by HWMA was calculated as the lifecycle benefit. Only the portion of the tipping fee that covers MSW disposal, $62.84 per ton, was included in the annual cash flow. It was also assumed these fees would increased annually at the general inflation rate. Using a cash flow table of annual system costs to annual benefits the discounted payback period and internal rate of return was determined for the alternative management systems.

The discounted payback period for investing in advanced waste management technologies was calculated from the annual net cash flows of lifecycle costs and life cycle benefit using the following formula:

$$\text{Discounted Payback Period} = n + \frac{ADC_n - ADB_n}{ADC_{n-1} - ADB_{n-1}}$$

n = period showing positive net cash flow (year)
$ADC_n$ = Accumulated discounted costs in period n
$ADC_{n-1}$ = Accumulated discounted costs in period before n
$ADB_n$ = Accumulated discounted benefits in period n
$ADB_{n-1}$ = Accumulated discounted benefits in period before n

(Hackett, 2012)

A modified internal rate of return was required to determine the rate of return for the LF P-MRF scenario because the annual cash flow reverts to negative within the lifecycle of the system.

$$MIRR\ (\%) = \sqrt[n]{\frac{FV\ (positive\ cash\ flows,\ \ reinvestment\ rate)}{-PV\ (negative\ cash\ flows,\ \ dicount\ rate)}} - 1$$

Discount rate = 3%
Reinvestment rate = 2%

FV = the real future value cash flow in the final period
PV = the real present value cash flow in the first period
n = periods (years)

(Hackett, 2012)

The equation below was used to determine the internal rate of return for each of the IGMS scenarios:

$$NPV = \sum_{n=0}^{N} \frac{C_n - B_n}{(1+r)^n} = 0$$

NPV = net present value
N = number of periods (years)
n = period (year)

$C_n$ = real costs in period n
$B_n$ = real benefits in period n
r = internal rate of return (%)

(Hackett, 2012)

The next chapter describes the results of the analyses used to determine the feasibility of the proposed solid waste management systems.

# CHAPTER 7. FEASIBILITY ANALYSIS RESULTS

These results presented in this chapter focus on the three areas contributing to feasibility. The first section outlines the diversion potential achieved by the different waste management scenarios. The next section describes the environmental impact of the proposed management systems relative to continued landfill disposal of MSW through an estimate of GHG emissions. The final section presents the results of a lifecycle cost analysis of the different management systems and the potential savings achieved by decreasing landfill disposal of solid waste.

## 7.1. Waste Diversion Potential

A solid waste MRF used in the alternative waste management systems would be able to reclaim recoverable materials that are not source separated by the public for diversion. The diversion potential of each of the alternative management systems was determined from historic HWMA throughputs and the Waste Characterization Study. The 2011 Waste Characterization Study, contracted to the Cascadia Consulting Group, Inc., was a partnership effort involving Humboldt County, the Trinidad Rancheria, the Blue Lake Rancheria, and Humboldt State University. The focus of this study was to identify potential diversion opportunities, provide a baseline for evaluating future diversion programs, and to create a foundation for HWMA's long-term solid waste management and resource recovery plans. See Figure 23 for pictures taken during the study.

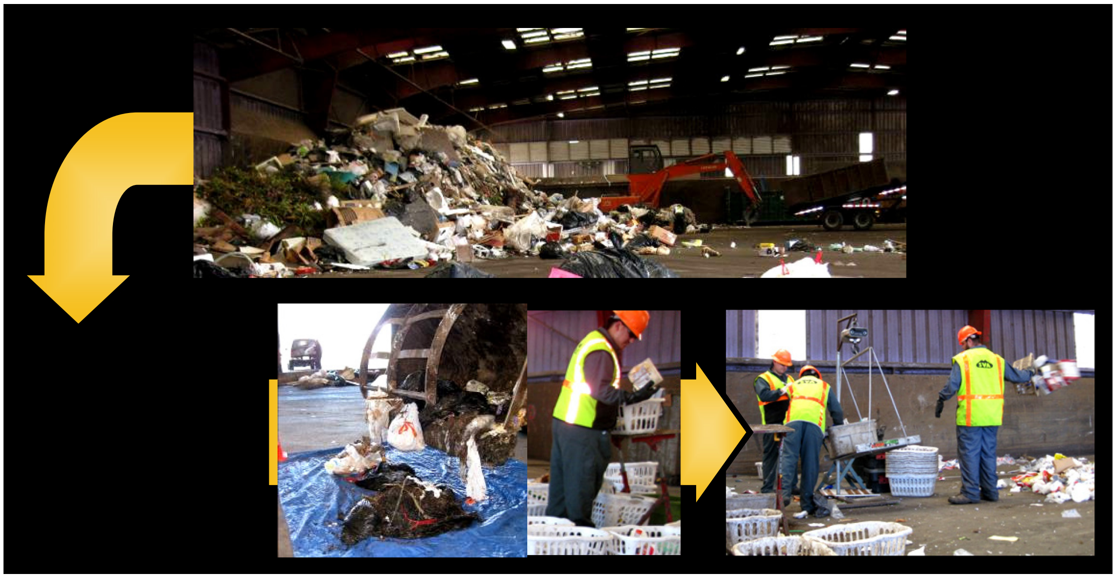

Figure 23. Images from 2011 Waste Characterization Study. Following the arrows, random 200-pound waste samples were isolated from randomly predetermined franchise and self-haul loads of MSW. Waste was manually sorted by material type into over 90 categories and recorded by weight.

The Characterization Study was conducted over two sessions in February and July of 2011. Over the course of the study, 202 random 200-pound waste samples were hand sorted and recorded by weight. The 88 samples of construction and demolition wastes were visually characterized, estimating the percent weight of the different materials present in the load. Random samples were taken from shipments from each of HWMA's six member agencies from four waste sectors: franchised commercial, franchised residential, self-haul, and construction and demolition debris. Each sample was separated into 90 possible categories by material type (Cascadia Consulting Group and HWMA, 2012).

The 90 material categories from the characterization study were grouped using a method illustrated in Table 11 to maximize material recovery and identify unrecoverable wastes that would be appropriate for gasification. The following options for waste treatment were identified from HWMA's current integrated waste management system and the possible implementation of AD and gasification: specialized disposal for HHW and UW, bulk recycling, mixed recycling, green waste composting, food waste composting, anaerobic digestion, gasification, and landfilling. From this methodology, the 90 materials categories were regrouped by diversion or disposal method.

Table 11. Example of method for matching waste streams to appropriate disposal or diversion method. The disposal methods across the top are listed in order of increasing environmental impact from left to right based on the U.S. EPA hierarchy for IWM. Boxes outlined in bold correspond with the assigned diversion or disposal method, where the acceptability of processing a material overlaps with the disposal method with the lowest environmental impact. Adapted from figure presented in (Youngs, 2011).

| | ← Lower Environmental Impact | | | | | |
|---|---|---|---|---|---|---|
| **Material** | **Alternative Disposal** | **Recycling** | **Compost** | **Anaerobic Digestion** | **Gasification** | **Landfill** |
| Paper/cardboard | NS | A | A | A | A | A |
| Painted wood | NS | NS | P | P | A | A |
| Textiles | NS | NS | P | P | A | A |
| Manure | NS | NS | P | A | AA | A |
| Bioplastics | NS | NS | P | P | A | A |
| Film plastics | NS | P | NS | NS | A | A |
| Glass | NS | A | NS | NS | P | A |
| Tires | A | NS | NS | NS | A | P |
| Used oil filters | A | NS | NS | NS | P | P |

| **Key** | Acceptable | Problematic | Not Suitable |
|---|---|---|---|

Similar to the findings of the Characterization Study, 35% of MSW was identified as potentially compostable and 23% as recyclable (Figure 24). Of the compostable materials fraction, 8% is green waste that can be processed at the compost site in Arcata. An anaerobic digester could accept 42% of the food waste, and the rest of the organic wastes could be processed at the nearest composting facility in Ukiah. From the fraction of MSW that is recyclable, 25% could be recovered and sold in bulk. These would include scrap metal, corrugated cardboard, and large pieces of rigid plastics. The last 75% is comprised of mixed recycling. Problem materials that are not practical to recycle make up 41% of what is currently landfilled. Composite materials constitute the majority of the residual, as seen in Figure 24 (b). The residual fraction consists of 43% biogenic wastes, which includes mixed organics but also portions of items like waxed paper cups or cardboard, treated wood, and textiles.

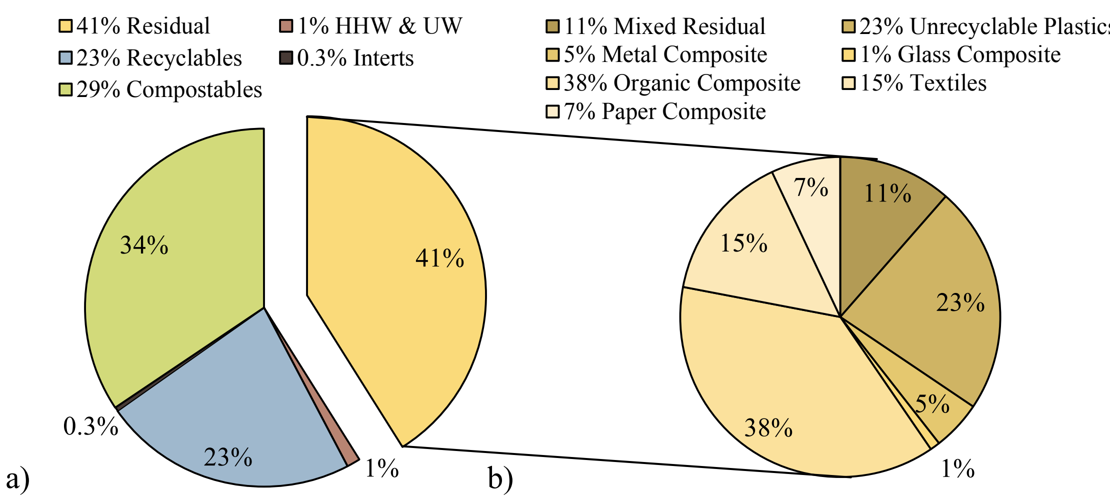


Figure 24. Designation of (a) divertible waste streams from MSW and (b) composition of residual stream. A complete list of materials in RDF is available in Appendix F, Table F.1.

HWMA diverted 16% of the total tonnage that passed through the Transfer Station in 2012, shown in Figure 25 (a) (Egerer, 2012b; Humboldt Waste Management Authority, 2013b).[45] Figure 25 (b) shows that combining these efforts with a dirty MRF could divert up to 65% of solid waste. This would decrease HWMA's waste disposal rate to 1.15 PPD and meet California's waste reduction goal of 2.7 PPD set by AB 341 (Edgar & Associates, Inc., 2012).

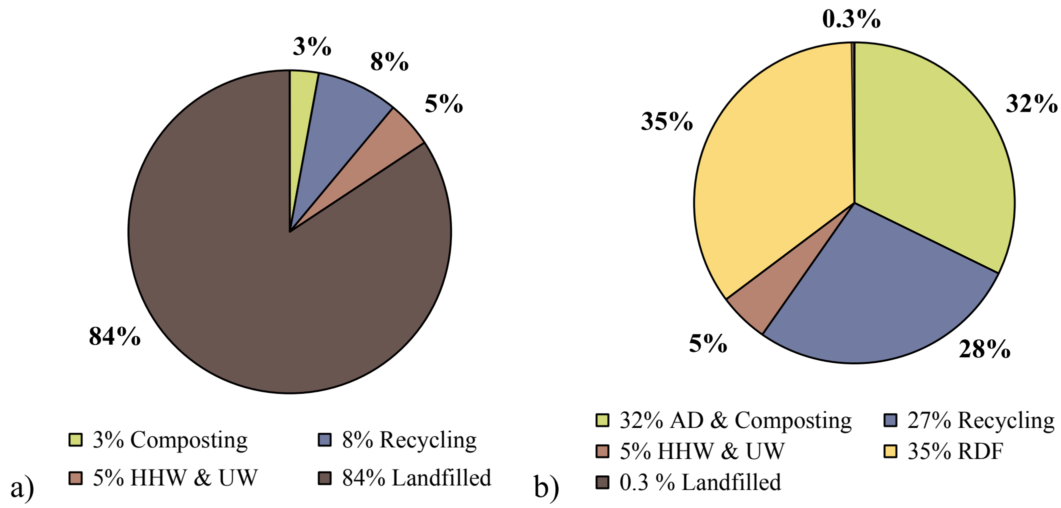


Figure 25. Comparison of current and potential waste diversion. a) 2012 FY waste diversion by HWMA of 16%. b) Potential waste diversion with IGMS that achieves 65% waste diversion and 99% diversion from landfill.

Gasification of residual is not considered waste reduction. Therefore, it does not contribute to the 65% diversion potential. However, implementing a local gasification system combined with these diversion efforts would dramatically decrease landfill disposal

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[45] This diversion rate is only representative of HWMA activities since HWMA only collects a portion of the county's recycling (Egerer, 2012c).

up to 99 percent. Inert wastes, mainly concrete, accounts for 0.3% of the Humboldt County waste stream by mass, and is the only portion of the waste stream that would need to be landfilled.

### 7.2. Electricity Production

The electricity generation potential of RDF depends on the energy density of the feedstock and the efficiency of the gasification system, which includes the capture of chemical energy from RDF and the conversion of syngas to electricity. The overall efficiency of the gasification systems and parasitic demands are not well documented in the literature and are highly specific to each gasification system.

To model the energy output of the Adaptive ARC system, the energy available in RDF was determined from the mix of materials and their typical energy densities. Based on assumptions listed in the methods, the higher heating value (HHV) of a wet ton of RDF is estimated to be 10.7 MMBtu. The estimated moisture content is 24%, making the HHV of a dry ton of RDF 12.8 MMBtu. Different sources reported in Chapter 5 estimate the overall energy density of MSW to ranges from 9.0 MMBtu to 11.74 MMBtu per dry ton (Garg et al., 2007; Kaplan et al., 2009). This is a little lower than the density calculated for the RDF, but this is to be expected since most of the inerts and high moisture content waste have been removed by the DirtyMRF.

AdaptiveARC's RFI response provided an overall system energy efficiency of 24%. This AdaptiveARC system uses two CAT 3516b LE engines that co-fire diesel with syngas from two ce25 gasification units (Damore & AdaptiveARC, Inc., 2012).

This CAT generator is rated at 1.64 MW of electricity at 100% load, have a diesel consumption rate of 119 gallons per hour, and an efficiency rating of 37% (Caterpillar Inc., 2011). Running on syngas, each generator's diesel consumption is reduced to 6.8 gallons an hour. The AdaptiveARC system also uses diesel fuel with syngas to power the plasma torches (Damore & AdaptiveARC, Inc., 2012). All together, the system uses 4.2 gallons of diesel fuel to gasify and convert one ton of waste into electricity, or 6.1 gallons per MWh.

At 24% moisture content, 8.79 MMBtu of energy per wet ton of RDF is required to run the generator at 100% load with the minimum diesel fuel requirements. Additional diesel fuel would be required to maintain a stable generation rate if there are dips in the energy quality of the feedstock. Taking into account the energy required to vaporize the water content in RDF, the net energy available for conversion to syngas is 10.23 MMBtu per wet ton of RDF, exceeding the minimum requirement by 16%.

In this energy model, the gensets are assumed to operate at nameplate capacity and efficiencies with the minimum diesel fuel requirements. From the model, the productive yield of the gasification system, after accounting for parasitic loads, would be 3.09 MW of electricity. Processing 28,144 tons, the Adaptive ARC system would annually produce 17.3 GWh of electricity.

Based on the assumption that on average RDF can provide sufficient energy to meet the generator specs, this analysis assumed a constant electrical output from the generators ignoring the fluctuations in feedstock quality that will occur. A sensitivity analysis is presented later to account for variations in moisture and energy content.

The AdaptiveARC system as a gasification technology processing post-MRF RDF could qualify as a renewable energy source according to the Renewable Portfolio Standard Eligibility Commission Guidebook released in 2012 by the California Energy Commission. The Guidebook also states that multi-fuel systems could be prorated for renewable eligibility by energy source (California Energy Commission, 2012). When running at steady state with the minimum diesel requirement, syngas provides 95% of the energy for electricity generation. This would qualify 2.87 MW of the 3.09 MW as renewable capacity. See Table 12 for annual electrical yields based on this generation scenario, IGMS (PR), that is used in both the GHG analysis and lifecycle cost analysis.

In the IGMS (BD) scenario, the AdaptiveARC system is modified to run on 100% biodiesel (B100). Under the California RPS, B100 produced from soybeans qualifies as a renewable energy source (California Energy Commission, 2012). This makes all the electricity generated by the AdaptiveARC system RPS eligible, but running B100 in a Caterpillar engine will decrease the generation efficiency (Williams, 2012). To account for this, the generation efficiency is reduced to 35% in this scenario and productive yield to 3.06 MW of electricity (Table 12).

Table 12. Annual electrical production for the different generation scenarios. The productive yield takes into account the parasitic load from the gasifiers. The electricity to grid takes into account HWMA loads including electrical demand of the solid waste MRF.

| | **Generation Scenario 1 (NR)** | **Generation Scenario 2 (PR)** | **Generation Scenario 3 (BD)** |
|---|---|---|---|
| Gross Yield | 17.8 GWh/yr | 17.8 GWh/yr | 17.6 GWh/yr |
| Productive Yield | 17.3 GWh/yr | 17.3 GWh/yr | 17.2 GWh/yr |
| Non-renewable to Grid | 16.5 GWh/yr | 1.2 GWh/yr | 0 GWh/yr |
| Renewable to Grid | 0 GWh/yr | 15.4 GWh/yr | 17.2 GWh/yr |

It is also assumed that the gasification system is able to offset loads at the HWMA Transfer Station including the dirty MRF. The compact size of the AdaptiveARC system would make it possible to site at the Hawthorn Street Facility which is sited on 4.3 acres of industrial land (Humboldt Waste Management Authority, 2013a). Together the electrical demand from all HWMA operations and a MRF is 763 MWh per year, only four percent of the annual generation (Atchison & CP Group of Companies, 2012; Harris & Sierra International Machinery, 2012; Jacobson, 2012). This leaves 90% of the gross electrical yield available to be sold to the grid.

The proposed AdaptiveARC system (110 tpd) exceeds the capacity requirement for Humboldt County's residual (80 tpd). Operation of this system for this analysis is therefore reduced from seven to five days a week. AdaptiveARC recommends a complete system shut down for two hours over the course of the work week (Damore, 2012). Shutdowns would conceivably occur in the middle of the night when the price on electricity is the lowest. This reduced schedule would still meet the electrical demand of HWMA during general operation hours.

### 7.2.1 Sensitivity Analyses

Solid waste is a challenging feedstock because it has a high variability in moisture and energy content. A sensitivity analysis (Figure 26) shows the influence of moisture content on available energy in RDF. AdaptiveARC reports their ce25 can accept up to 50% moisture content, but this analysis determined RDF at less than 35% moisture content is required to maintain the minimum energy demand of the generator from syngas. At levels above 40%, a 10% increase in moisture content reduces the available energy for conversion to syngas by 1.26 MMBtu. From this sensitivity analysis, the removal of wet waste that is achieved by diverting pre and post-consumer food waste greatly increases the efficiency of this system.

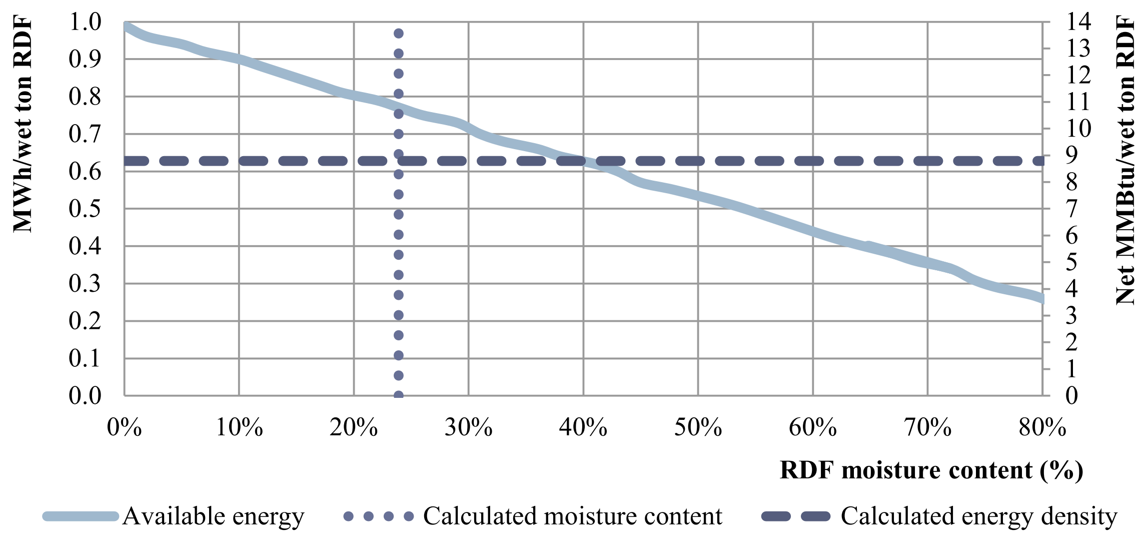



Figure 26. Sensitivity of generation rate from RDF to variations of moisture content. The estimated average moisture content and generation rate of RDF are shown as dotted lines. The ‘Calculated energy density’ describes the minimum energy demand from syngas to operate the generator at 100% nameplate electrical capacity.

Figure 27 shows the change in diesel fuel demand in response to feedstock quality. The minimum diesel fuel requirement for the generator is 6.8 gallons per hour. Based on the sensitivity analysis for energy content, it can be seen that increased moisture levels not only decrease efficiency but would also increase diesel fuel consumption to maintain maximum power output. A reduction of one MMBtu of energy per ton of RDF, which is roughly equivalent to the energy in two tons of carpet, increases the diesel consumption by approximately 12.7 gallons. As shown in the earlier analysis, one MMBtu is equivalent to the energy required to vaporize 158 pounds of water or 19 gallons.

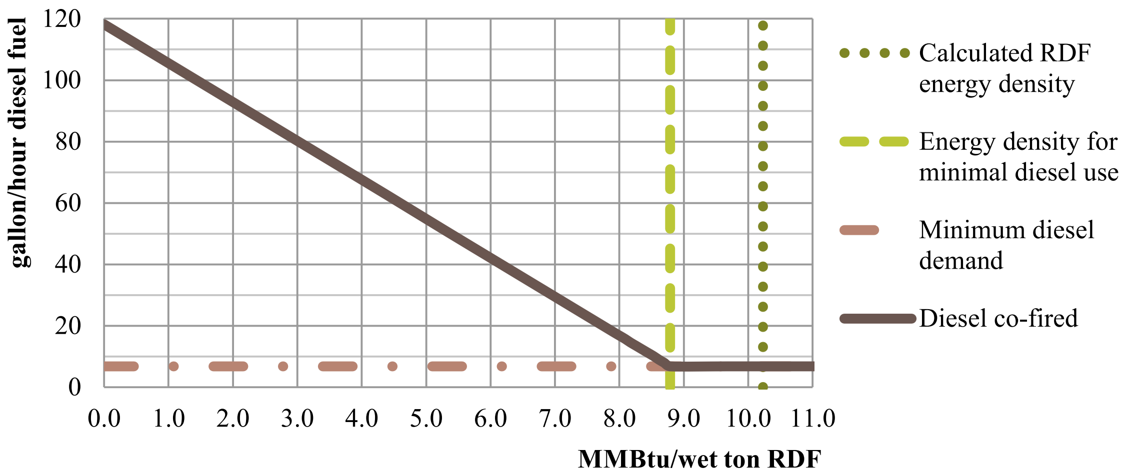



Figure 27. Sensitivity analysis of diesel consumption with varying energy densities of RDF. The figure shows the diesel consumption rate of a single generator. Shown by a dashed and dotted line, the minimum diesel fuel requirement is 6.8 gallons per hour. The ‘Calculated RDF energy density’ shows the energy content assumed for Humboldt RDF. The ‘Energy density for minimal diesel use’ is based on the specs for the generator. This sensitivity analysis does not take into account the possibly of turning the generator to a lower load setting for extended batches of low quality RDF.

### 7.3. Comparison of Greenhouse Gas Emissions Assessments

This assessment compares the GHG emissions produced by the alternative waste management systems to a baseline of continuing to landfill all MSW. The three scenarios for comparison have alternative methods of residual disposal: landfilling residual (LF P-MRF), gasification of residual and co-firing syngas with diesel for electricity production (IGMS), and gasification of residual and co-firing biodiesel with the syngas to produce electricity (IGMS BD).

The GHG emissions of each scenario are estimated over a 20-year period. It is common to report GHG emissions on a 100-year basis, but the shorter 20-year period was chosen to correspond with the lifecycle cost analysis that follows. The global warming potential (GWP) value is a comparative measure of how much heat a particular GHG traps in the atmosphere compared to the heat trapped by carbon dioxide by mass (United Nations Framework Convention on Climate Change, 2012). In the case of methane and nitrous oxide, the GWP value is different over these time periods due to their atmospheric lifetime (Table 13). Converting different GHG using their respective GWP provides a way to present emissions as in a single unit of carbon dioxide equivalent ($CO_2e$).

Table 13. Global warming potentials of common greenhouse gases over different time periods. Data source: (United Nations Framework Convention on Climate Change, 2012)

| | Lifetime | GWP over 20 Years | GWP over 100 Years |
|---|---|---|---|
| Carbon Dioxide ($CO_2$) | variable | 1 | 1 |
| Methane ($CH_4$) | 12 ± 3 years | 56 | 21 |
| Nitrous Oxide ($N_2O$) | 120 years | 280 | 310 |

The emissions included in this assessment are Scope 1 and Scope 2 emissions, as defined by the Greenhouse Gas Protocol, limited to operations of MSW management. Scope 1 emissions include direct emissions, which are emissions produced by sources owned or controlled by the reporting entity, in this case HWMA. Scope 2 emissions include indirect emissions. These are emissions attributed to the reporting entity's activities but occur at sources owned by a different entity, such as emissions produced to generate electricity that is purchased by the reporting entity (Greenhouse Gas Protocol, 2012).

There are other environmental impacts attributed to landfill disposal that may be avoided through the use of alternative disposal methods. Soil and water pollution, demand for raw materials and soil amendments, and changes in land use are significant impacts but are challenging to quantify. Similarly, this is the case for criteria pollutants produced from the combustion of diesel fuel, syngas, and biogas. For these reasons and because of the long-term and global impact that GHG emissions have on climate change, the accounting of environmental impact is limited to GHG emissions.

The GHG emissions inventoried for the scenario of continuing to landfill all MSW included Scope 2 emissions of hauling waste to landfills and production of landfill gas. A list of emission sources by scope for each of the management scenarios is provided in Table 14. Other HWMA Scope 1 and 2 emissions are assumed to remain static and are not inventoried in this analysis. This would include direct emissions from heavy equipment or purchased electricity used at the Hawthorn Transfer Station.

Scope 3 emissions are also not included in this boundary, for example: use of heavy-duty vehicles or utilization of captured landfill gas at the different landfill sites.

To process 68,544 tons of MSW requires 3,254 trips to the landfills annually. From the estimated 4.3 miles per gallon fuel economy of the Bettendorf Trucking Company fleet and estimating each truck has a 21 ton capacity, the diesel required to transport 1 ton of waste to the landfill produces 41 kilograms (kg) $CO_2e$ emissions (Bohn, 2010).

Landfill gas produced from Humboldt solid waste will add 523,491 metric tons of carbon dioxide equivalent emissions ($tCO_2e$) emissions to the atmosphere over 20 years. These emissions were calculated from a method provided by the Climate Action Reserve protocol (Climate Action Reserve, 2011). Because of the high global warming potential of methane, landfill gas production accounts for 90% of emissions from the LFD scenario.

In total, continuing to landfill all MSW for 20 years produces 580,073 $tCO_2e$ emissions. Levelized by MSW throughput, this disposal option has a carbon intensity of 423 kg $CO_2e$ per ton of waste.

The models for the alternative waste management systems of LF P-MRF and IGMS take into account Scope 1 and 2 emissions, which are listed in Table 14. This includes emissions from HWMA satellite operations of green waste composting and anaerobic digestion.

Table 14. List of emission sources by scope for different components of waste management. The analysis includes inventories of only Scope 1 and Scope 2 emissions. The Integrated Gasification Management System includes emissions from both the dirty MRF system and gasification system.

| | Scope 1 | Scope 2 | Scope 3 |
|---|---|---|---|
| **Landfill Disposal** | ▪ None within boundary of management system | ▪ Emissions from transportation fuels used to haul waste materials to the landfills<br>▪ Production of landfill gas | ▪ Utilization of collected landfill gas<br>▪ Use of heavy machinery at landfill sites |
| **Dirty MRF System** | ▪ Methane production from green waste composting<br>▪ Emissions from waste materials processed by anaerobic digestion | ▪ Emissions from transportation fuels used to haul waste materials<br>▪ Emissions from waste materials diverted to composting site<br>▪ Emissions produced by generation of purchased electricity<br>▪ Production of landfill gas | ▪ Offset use of raw material manufacturing by recyclables<br>▪ Offset use of soil amendments<br>▪ Production of equipment for MRF<br>▪ Employee commutes |
| **Gasification System** | ▪ Emissions from the combustion of syngas<br>▪ Emissions from the combustion of liquid fuels Emissions from combustion of propane | • Emissions from transportation of ash | ▪ Offset use of additives for cement<br>▪ Production of AdaptiveARC system |

Emissions from advanced thermal treatment of biogenic waste were inventoried according to the Accounting Framework for Biogenic Carbon Dioxide Emissions from Stationary Sources released in 2011 by the U.S. EPA. This framework prescribes the use of a multiplier or biogenic accounting factor (BAF) to describe the timeframe of the carbon cycle of different emission sources. Under this framework, composting, anaerobic digestion, and gasification of biogenic waste are all assigned a BAF of zero. A zero BAF infers that these activities do not contribute to net increase in atmospheric concentrations of GHG because emissions produced are balanced by offset factors in their lifecycle (U.S. Environmental Protection Agency, 2011).

While not considered long-term contributions to atmospheric carbon, the GHG emissions from composting and anaerobic digestion are much lower per unit waste than landfill disposal. Composting 11,816 tons of waste each year at either Wes Green or Cold Creek produces 3,745 $tCO_2e$ annually from emissions of carbon dioxide, methane, and nitrous oxide. This value was determined using an emission factor for open-air composting estimated by the IPCC (Intergovernmental Panel on Climate Change, 2006). From an IPCC emissions factor for anaerobic digestion, processing 10,000 tons of food waste with energy recovery produces 508 $tCO_2e$ emissions. The emissions from digestion are much lower than composting since methane is captured and combusted into carbon dioxide. Diversion of organic wastes to these facilities produces 85,061 $tCO_2e$ compared to 272,291 $tCO_2e$ produced over 20 years from landfilling this waste.

To estimate emissions produced by transporting the different diversion streams, the trucks were assumed to operate at a fuel efficiency similar to Bettendorf Trucking Company. Transportation distances of the individual waste fractions are listed in Table 15. Household hazardous and universal wastes travel the furthest for disposal. The rest of the diverted materials are processed at facilities that are all closer than the Anderson and Dry Creek Landfills.

Table 15. Destinations and distances for diversion or disposal of different materials.

| Material Transported | Destination | Distance to Destination |
|---|---|---|
| Landfill disposal | Dry Creek Landfill in White City, OR<br>Anderson Landfill in Anderson, CA | 184 miles (weighted) |
| Green waste for composting | Wes Green in Arcata, CA | 13 miles |
| Biogenic waste for anaerobic digestion | Digester Site in Eureka, CA | 3 miles |
| Biogenic waste for composting | Cold Creek Composting in Ukiah, CA | 155 miles |
| Mixed recycling | Solid Waste of Willits in Willits, CA | 134 miles |
| Household hazardous and universal wastes | Multiple destinations | 1136 miles |
| Gasifier ash | Cement processing in Sacramento, CA | 290 miles |

The GHG emissions produced by the LF P-MRF management system, where only residual waste is landfilled, are much lower than the baseline LFD scenario. The landfill gas produced from landfilling only residual waste produces 165,465 $tCO_2e$ in emissions over 20 years. This is a 68% reduction from landfill gas emissions produced by the LFD scenario. This reduction is proportionately higher than the amount of waste that is diverted (58%) because of the reduced concentration of biogenic wastes in the residual that is sent to the landfills. Levelized over the total MSW throughput, the carbon intensity of the LF P-MRF system is 156 kg $CO_2e$ per ton of MSW (see Figure 28).

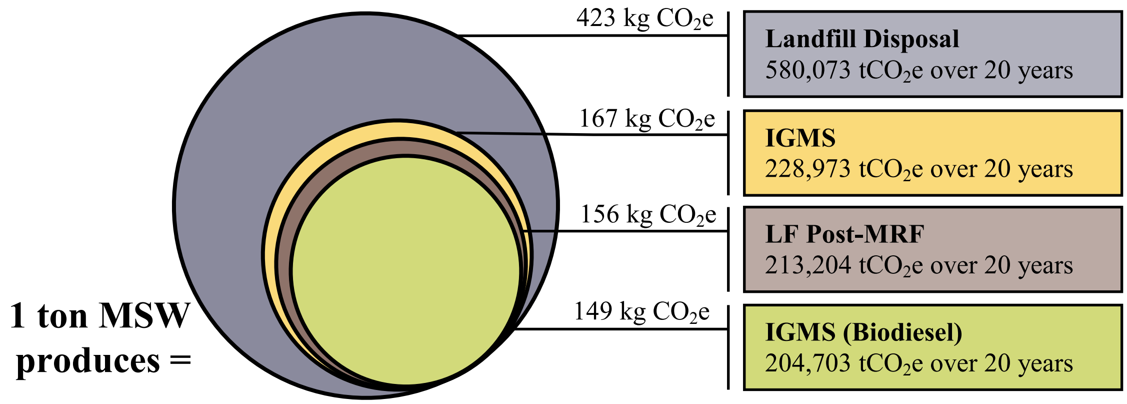



Figure 28. Emissions of each waste management system over 20 years and levelized for total MSW throughput.

In the case of the IGMS, GHG emissions are reduced by 61% relative to LFD. In this scenario, emissions from transportation are reduced by 50% compared to landfilling residual, and the emissions from combustion of syngas are the largest contributor to the total emissions. Based on the carbon balance for the combustion of syngas, it is estimated that the electricity produced by the AdaptiveARC system would have a carbon intensity of 0.93 $tCO_2$e per MWh. Taking into account the BAF for the 46% of biogenic waste in a dry ton of RDF, the adjusted emissions rate is 0.53 $tCO_2$e per MWh. Levelized over 20 years, IGMS would produce 167 kg of $CO_2$e per ton of waste (see Figure 28).

Altering the generation system of the gasification system in the IGMS to run 100% biodiesel would provide a reduction in emissions of 65% relative to the LFD scenario. The emissions rate for electricity produced in the IGMS (BD) scenario, after applying the BAF for syngas from biogenic sources and biodiesel, is 0.48 $tCO_2e$ per MWh, and has a system-wide carbon intensity of 149 kg $CO_2e$ per ton of MSW.

Accounting for the offset of local generation of electricity by the electricity produced by AD and the gasification system would further decrease the environmental impact of the alternative waste management systems. The offset generation is assumed to be from the Humboldt Bay Power Plant since it provides 51% of the electricity for the county. The Humboldt Bay generation station consists of 10 reciprocating engines running on natural gas with some distillate fuel oil, and has a total capacity of 163 MW. The plant was designed to provide backup to intermittent renewable sources, which were being planned at the time of implementation. From operational data, the carbon intensity of this electricity is estimated at 0.49 $tCO_2e$ per MWh (Pacific Gas and Electric Company & The California Energy Commission, 2013). The other sources of electricity for the County are biomass power plants, which meets 25% of the electricity demand, electricity imported from outside the region by Pacific Gas and Electric, which provides 19%, and electricity from hydropower, which accounts for 5% (Schatz Energy Research Center, 2013; Zoellick et al., 2005).

Taking into account this avoided generation from the Humboldt Bay Generation Station, emissions from MSW management are reduced from the baseline LFD scenario by 67% for the LF P-MRF scenario, 96% for the IGMS scenario, and 100% for the IGMS (BD) scenario. A comparison of emission sources and avoided emissions for each management system is presented in Figure 29.

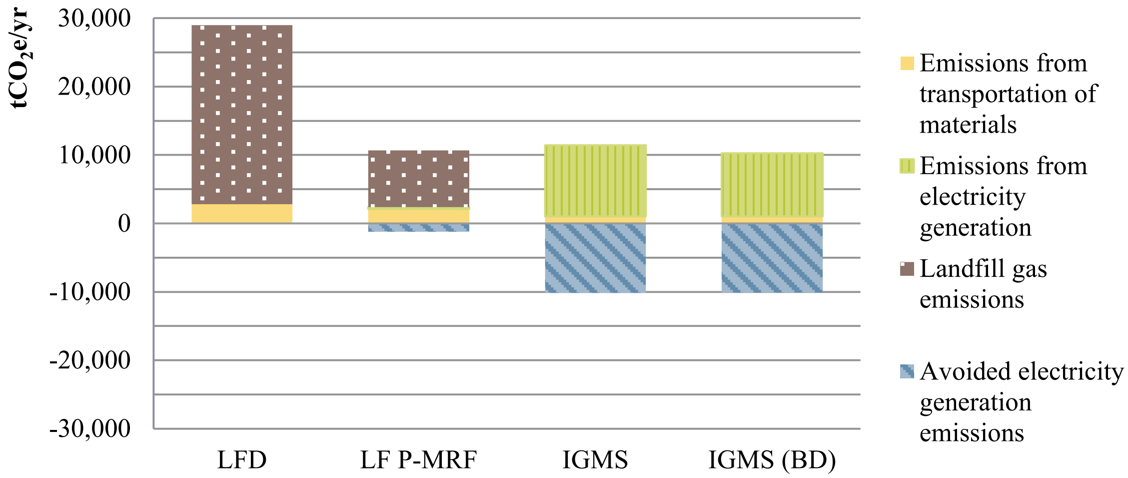



Figure 29. Levelized annual emissions by source for different waste management systems.

This GHG analysis identifies that, while waste from Humboldt is hauled a long distance for disposal, transportation contributes less than 10% of the total emissions produced from continuing to landfill MSW. Diverting waste does reduce transportation emissions because the processing sites are generally closer than either of the landfills, but the most significant reductions in emissions are achieved by avoiding the production of landfill gas.

As can be seen in Figure 29, landfilling residual waste compared to gasification operating with diesel fuel produces less carbon emissions, even when only accounting for non-biogenic sourced emissions from gasification system. However, when avoided emissions from natural gas based electricity generation are included, integrated gasification provides close to a carbon neutral option for MSW disposal.

### 7.4. Lifecycle Cost Comparison

For this lifecycle cost analysis (LCC) cash flows for each of the alternative waste management systems were modeled over 20 years. This analysis only accounts for the processing of MSW, similar to the system boundary used for the GHG analysis. All other HWMA operations are assumed to remain the same for all scenarios. The LCC is calculated with a real discount rate of 3%. The rate of general inflation was set at 2.5%. Pricing for diesel fuels, electricity, and water were escalated at rates of 6.3%, 1.5%, and 7.7% respectively. Line item unit costs for model inputs are listed in Appendix G along with the basis for these assumptions. Appendix H contains tables of cost and revenue streams for the different scenarios, and lists the applied escalation rates.

The LCC of continuing to landfill all MSW is projected as $85.9 million. This LCC includes the cost of transportation at $35.68 per ton and the landfill-tipping fee of $20.70 per ton for discarding MSW at the Anderson and Cold Creek Landfills. Costs and revenue sources for this scenario are listed in Appendix H, Table H.1.

The current contracts with HWMA fixes the tipping fee charged by the landfills. Both these contracts are up for negation in 2014 and 2015, and a sensitivity analysis for the landfill-tipping fee is provided later in this section. HWMA’s contract for waste hauling waste includes a fixed fee and a fuel surcharge. In the model, the transportation costs in this LCC increase at the fuel escalation rate. The levelized cost of disposal (LCOD) for LFD is $84.25 per ton of MSW taking into account a discounted lifecycle cost and throughput. This value is representative of the tipping fee HWMA would need to charge for MSW disposal to recover costs of this solid waste management system.

Over twenty years of operation, the LCC of LF P-MRF is estimated at $81.4 million (see Figure 30). The cost of implementing a solid waste MRF is $4.9 million including equipment, installation, development and permitting, and a 30% contingency. In this system, the majority of waste is still transported out of county, but the annual cost of transportation is reduced, since more than half of MSW is transported to diversion sites that are closer than the landfills. As with LFD, transportation and tipping fees continue to account for the majority of the costs of operating this management system (see Figure 31).

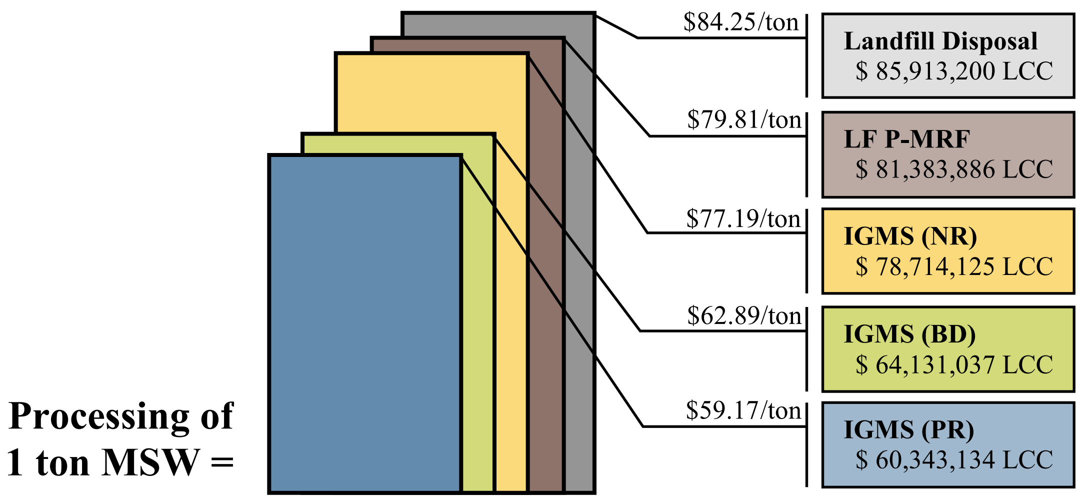



Figure 30. LCC for landfill disposal and alternate management systems. The levelized cost of disposal is shown in dollars per ton and the LCC is over the 20 years of operation.

Compared to landfilling all solid waste, this system would reduces the LCC of MSW management by $4.5 million. With the additional costs of electricity, equipment and maintenance costs for the MRF, and wages to staff operation of this system is more expensive than the LFD scenario. The $4.5 million in revenues are achieved by the income from bulk and mixed recycling separated from MSW. Costs and revenue sources for this scenario are listed in Appendix H, Table H.2. The LCOD for the LF P-MRF scenario is $79.81 per ton.

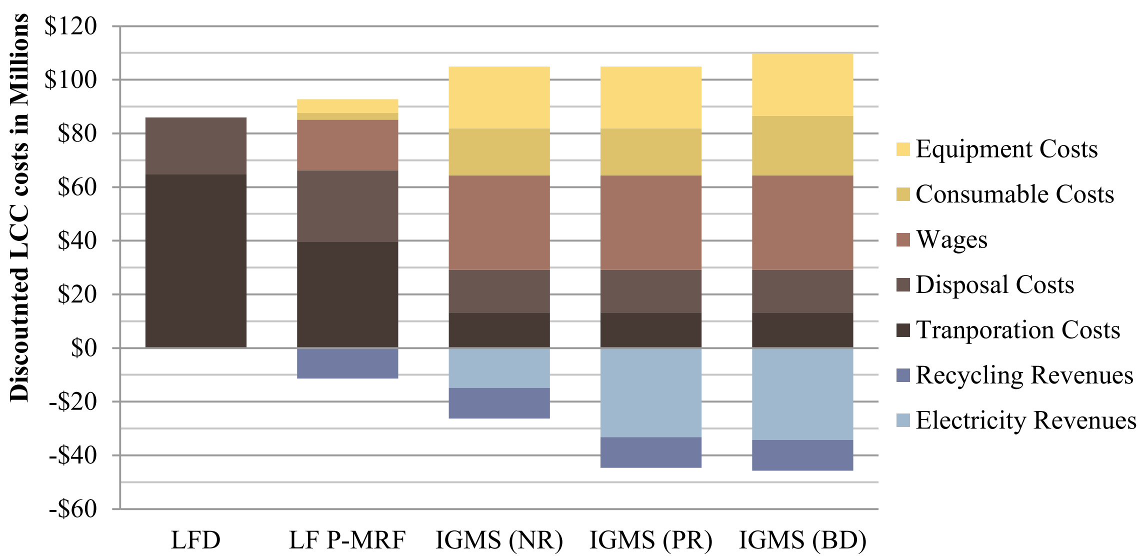



Figure 31. LCC broken down by costs and revenues sources for each management system. By including revenue streams from recycling and electricity the LCC of operating the IGMS system is much lower than the cost of continuing to landfill as MSW. This figure also shows that the IGMS (BD) operates at a higher cost than IGMS (NR) because of the increased cost of consumables and maintenance for operating the system with biodiesel.

The total cost of implementing an integrated system is $22.0 million, which includes installing a dirty MRF, permitting and site development, and a 30%

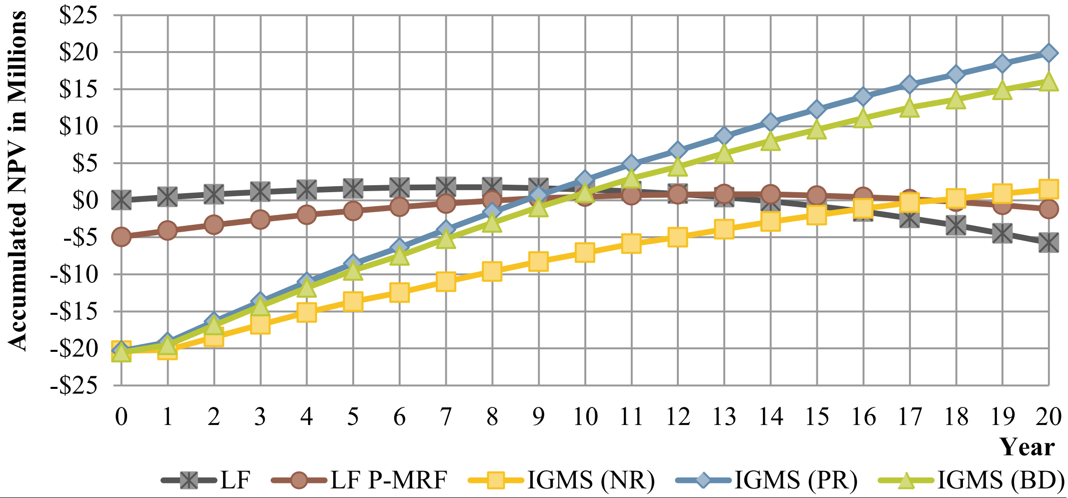
contingency. Ongoing costs for the gasification system, in addition to the MRF operations and cost of diversion, include major equipment replacements, wages, consumables, fuels for operating the gasification system, and ash disposal. There are two direct revenue sources from this system, sale of recyclable materials and sales of electricity to the grid. To account for offset costs of electricity for HWMA Transfer Station and MRF by electricity from the gasification system, the revenue of this electricity is valued at the retail rate. The revenue rate for the electricity produced by the gasification system that is sold to the grid, is dependent on the renewable energy classification status. A complete list of model inputs is listed in Appendix G, Table G.1.

The LCC of IGMS (NR) is $78.7 million, $7.2 million less than continued landfill disposal of MSW. This system has a LCOD of $77.19. This system sells 18,182 MWh of electricity annually to the grid at the wholesale rate of $39.86 per MWh. Shown in Figure 31, a large portion of this system's costs are attributed to wages for employees to operate the MRF and gasification systems. Costs and revenue sources for this scenario are listed in Appendix H, Table H.3.

With renewable classification for electricity from syngas in IGMS (PR), the revenues from electricity are greatly increased. The annual electricity revenue for the gasification system is $1.4 million. The electricity is prorated by energy source, with 92% of the energy eligible for the RPS and selling at $104.31 per MWh. Including this increase in revenue, the LCC of IGMS (PR) is $60.3 million, $25.6 million less than landfill disposal. The LCOD for this system is projected at $59.17 per ton.

Co-firing biodiesel with syngas to produced 100% RPS eligible electricity in the IGMS (BD) scenario has a LCC of $64.1 million. Modifications to the gasification system for biodiesel compatibility increase implementation costs to $22.3 million. This includes alterations to the generator sets and plasma torches as well as installation of circulation tanks and pumps needed for properly storing biodiesel. Biodiesel is also more expensive than regular diesel and the generator sets would require more frequent maintenance. This system operates at lower generation capacity, but revenues from electricity are higher than the prorated gasification scenario because all electricity is sold at the higher renewable rate. The LCOD of this system is $62.89 per ton MSW.

Using the current portion of the HWMA MSW tipping fee as a lifecycle benefit for solid waste management provides an annual net cash flow for identifying possible system payback periods and an internal rate of return (IRR) on investments. Processing 68,544 tons per year of MSW provides a discounted lifecycle benefit of $80.2 million. Figure 32 compares annual accumulated net present value (NPV) cash flows over the life of the different waste management systems.




| | | | | |
|---|---|---|---|---|
| **Internal Rate of Return** | 1.3%* | 3.8% | 12% | 10% |
| **Discounted Payback Period** | 8.1 years | 18 years | 8.7 years | 9.5 years |

*this is a modified internal rate of return

Figure 32. Accumulated NPV of lifecycle benefits and costs of different management systems over 20 years. The table below the graph presents the internal rates of return and discounted payback periods for each of the alternative management systems. Negative cash accumulations show the system operating at a deficit and positive cash accumulation shows the system operating at a net gain.

Under this revenue scheme, the costs of LFD will exceed tipping fee income in year eight. The initial capital investment of the LF P-MRF scenario is paid off in eight years, but like LFD will have costs exceeding tipping fee revenues in year 14 and in year 18 would operate at a deficit. In comparison, all the integrated gasification management systems are able to operate at a profit maintain HWMA's current MSW tipping fee. The IGMS (NR) has a discounted payback period of 18 years and a 3.8% IRR. Selling electricity from the gasification system at renewable rates accelerates the discounted payback period to 8.7 years for IGMS (PR) and 9.5 years for IGMS (BD). Both these scenarios have an internal rate of return over 10%.

**7.4.1 Cost Sensitivity Analysis**

Figures 33 through 42 show sensitivity analyses performed for different assumptions used to determine the LCC of each waste management system. These analyses summarizes the LCC as the LCOD as a more practical metric of comparison.

The first sensitivity analysis (Figure 33) shows the cost of each system responding to different throughputs of MSW. In this case, the change in tonnage assumes no change in the material characterization of MSW. The LCOD for continued landfilling remains level because of the linear cost structure of landfill disposal. All of the alternate scenarios experience an economy of scale at higher tonnages. In this analysis, wages for operating both systems were adjusted with processing demand. At MSW tonnages below 50,000 tpy the gasification system is operating at 51% capacity and processing less than 20,550 tpy. At these low feedstock rates, LCOD for IGMS (NR) exceeds the cost of LF disposal. Comparatively, at 40,000 tpy the IGMS (PR) and IGMS (BD) scenarios also experience a rise in operational costs but maintain a LCOD of less than $80 per ton.

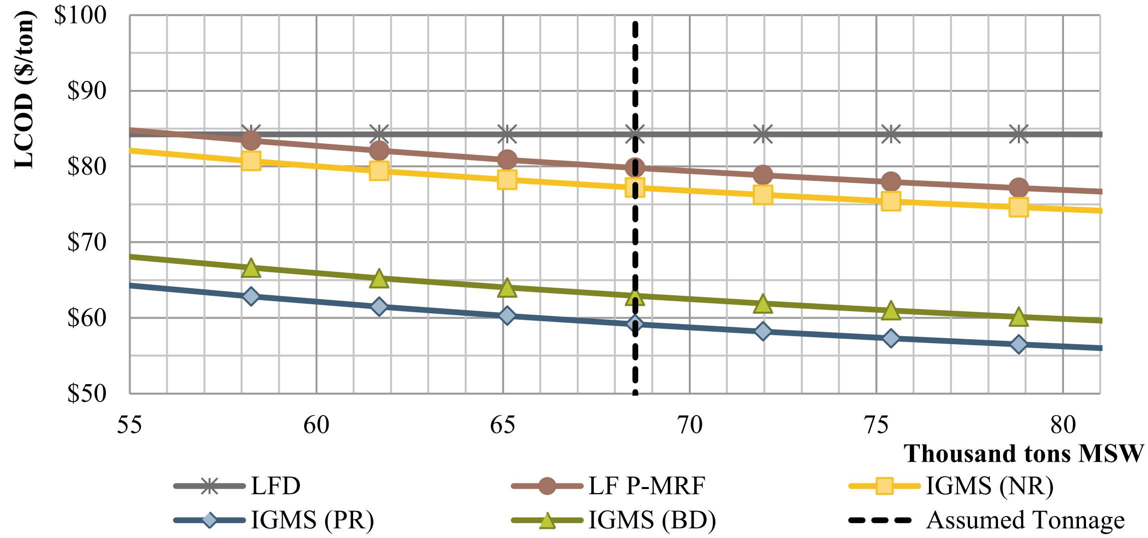



Figure 33. Sensitivity analysis of annual MSW throughput. HWMA's highest throughput in the last 10 years was 87,962 tons over the 2004 FY and the lowest was 65,354 tons over the 2011 FY (Sherman, 2012).

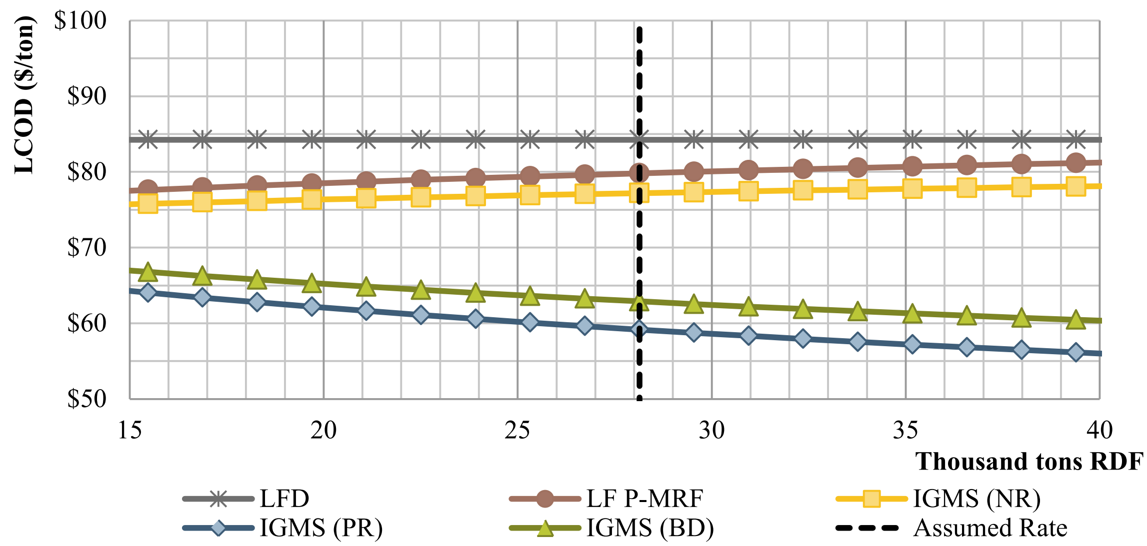



Figure 34. Sensitivity analysis of RDF tonnage. The AdaptiveARC system capacity is 40,000 tons per year.

The sensitivity analysis shown in Figure 34, adjusts the amount of residual in the waste stream while the amount of diverted materials remains at 40,175 tons per year. In this analysis wages were again adjusted to material throughputs. The RDF tonnage on the y-axis in Figure 34 closely correspond the total throughputs in Figure 33. Compared to the LCOD presented Figure 33, the LCOD of the alternative management systems this sensitivity analysis are less than the LCOD of LFD even at low total MSW throughputs. Here the LF P-MRF and IGMS (NR) scenarios are shown to operate at a lower cost as the portion of divertible waste increases relative to the portion of RDF. The two other scenarios also have only a slight decrease in the LCOD in Figure 34 at lower RDF tonnages.

These sensitivity analyses suggest that at tonnages below the current average, increased diversion rates are more economical in all of the alternative management systems. The different operational costs shown in Table 16, explain why this is the case. In this table, the cost of pretreatment by the MRF is shown separately, followed by the levelized cost of diversion, and gasification with their respective revenues. Gasification has the most expensive cost of operation when including the costs of implementing the system. However, revenues from electricity sold at renewable rates makes the net operational costs of gasification less than landfill disposal on a per ton basis. Processing materials for diversion has the lowest net cost, including revenues from recyclables. When including the cost of preprocessing by the MRF, divertible materials cost approximately of $55.50 per ton to process. Therefore, diverting a larger portion of MSW can decreases the overall system costs in each of the alternative management systems.

Table 16. Isolated costs and revenues for operation of individual waste treatments or disposal methods. These operational rates include the costs for installation, major equipment repair, and typical operations and maintenance levelized over the amount of materials processed over the lifecycle of the system.

| System Components | Levelized Discounted Costs $/ton | Levelized Discounted Revenues $/ton | Net Cost $/ton |
|---|---|---|---|
| Landfill Disposal of MSW (transportation costs and fees) | $84.25 | | $84.25 |
| Operation of Solid Waste MRF (installation and O&M) | $25.97 | | $25.97 |
| Diversion of Recoverable Materials (transportation costs and fees) | $48.49 | $18.96 | $29.53 |
| Gasification of RDF (NR) (installation and O&M) | $135.85 | $35.48 | $100.37 |
| Gasification of RDF (PR) (installation and O&M) | $135.85 | $79.35 | $56.50 |
| Gasification of RDF (BD) (installation and O&M) | $162.03 | $82.03 | $80.00 |

The next three figures show sensitivity analyses for the discount and inflations rates for fuel and electricity. In Figure 35, both the lifecycle cost and MSW tonnages are adjusted by the discount rate since the LCOD discounts the annual number of tons of MSW processed over the lifecycle of the systems. The integrated gasification systems show an increase in the LCOD at higher discount rates because of the high upfront implementation costs of this system. Both the LFD and LF P-MRF scenarios show a decrease in LCOD at a higher discount rate, because these system have less investment costs to recover.

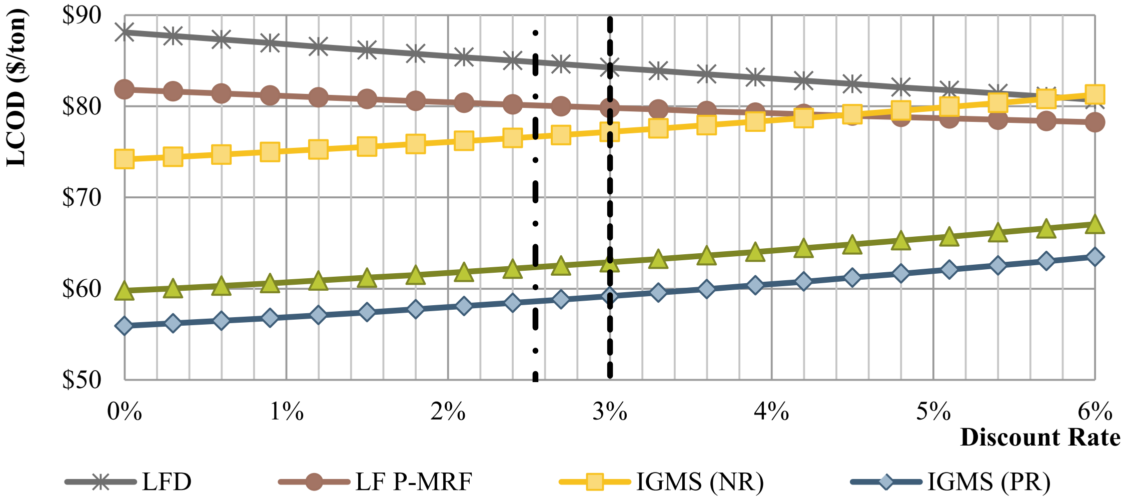



Figure 35. Sensitivity analysis of discount rate.

When adjusting the fuel escalation rate for, shown in Figure 36, all management systems responded with increased LCOD. Comparatively, landfill disposal and LF P-MRF reacted more steeply showing they are more vulnerable to changes in fuels cost.

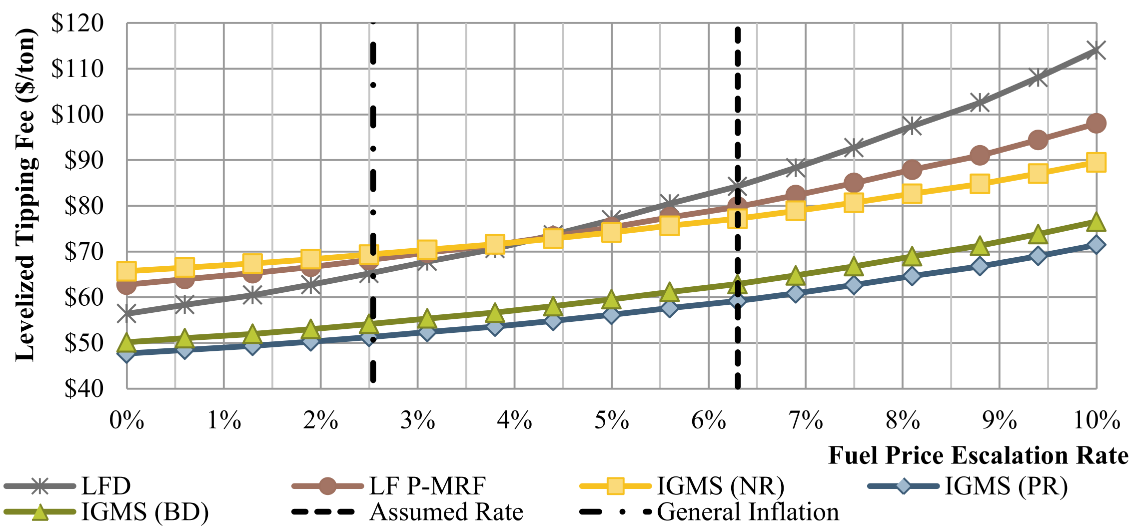



Figure 36. Sensitivity analysis of fuel inflation rate.

Comparing the diesel requirements of each scenario, IGMS has the lowest diesel fuel demand per ton of MSW (see Table 17). LF P-MRF decreases fuel demand compared to LFD. Diversion streams created by the dirty MRF are continue to transported out of the county, but to closer locations than the two contracted landfills. The average fuel requirement to transport diverted materials is 2.5 gallons per ton, compared to 4.1 gallons required transport a ton of waste to the landfill. The diesel consumption of the AdaptiveARC system is 4.2 gallons per ton, but the majority of this fuel is converted into electricity. The gasification system's diesel consumption rate is greater than the requirement for landfill disposal. Though the actual requirement for LFD is higher than what is shown here, since diesel use at the landfill is not included. Yet when demand for diesel fuel is averaged for all MSW processed by IGMS, it provides the least diesel intensive management system.

Table 17. Diesel fuel requirements of waste management systems. For IGMS the diesel fuel requirements for transporting diversion streams and the gasification system are presented individually, as well as the average demand for the system.

| | LFD | LF P-MRF | IGMS | Transportation of Diverted Materials | AdaptiveARC Gasification System |
|---|---|---|---|---|---|
| Diesel Fuel Demand (gallons/yr) | 278,731 | 233,871 | 222,478 | 103,054 | 119,424 |
| Diesel Fuel Consumption Rate | 4.1 gallons per ton MSW | 3.4 gallons per ton MSW | 3.2 gallons per ton MSW | 2.5 gallons per ton | 4.2 gallons per ton RDF |

Increasing the inflation rate for electricity does not have a dramatic effect on the different scenarios, as can be seen in Figure 37. The LCOD of the IGMS is most responsive when electricity from the system is sold at renewable rates.

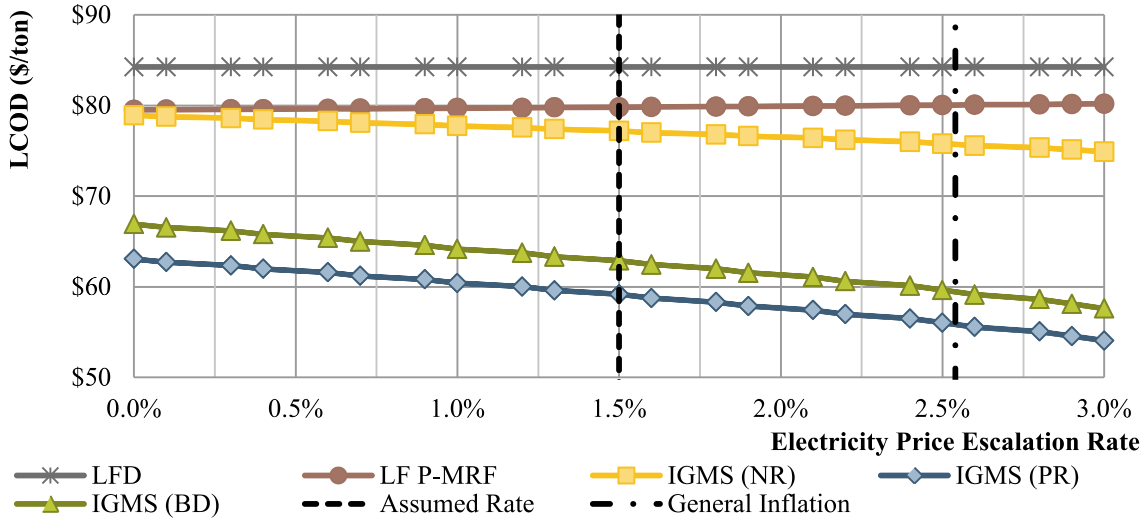



Figure 37. Sensitivity analysis of electricity price escalation rate.

The sensitivity analysis shown in Figure 38 shows the LCOD for the different management systems in response to higher landfill tipping fees. HWMA's landfill contracts will be up for renewal in 2014 and 2015 and fees could possibly increase from $5 to $10 per ton. At a $30 per ton landfill tipping fee, the LCOD for IGMS (PR) is $34.36 less per ton than LFD.

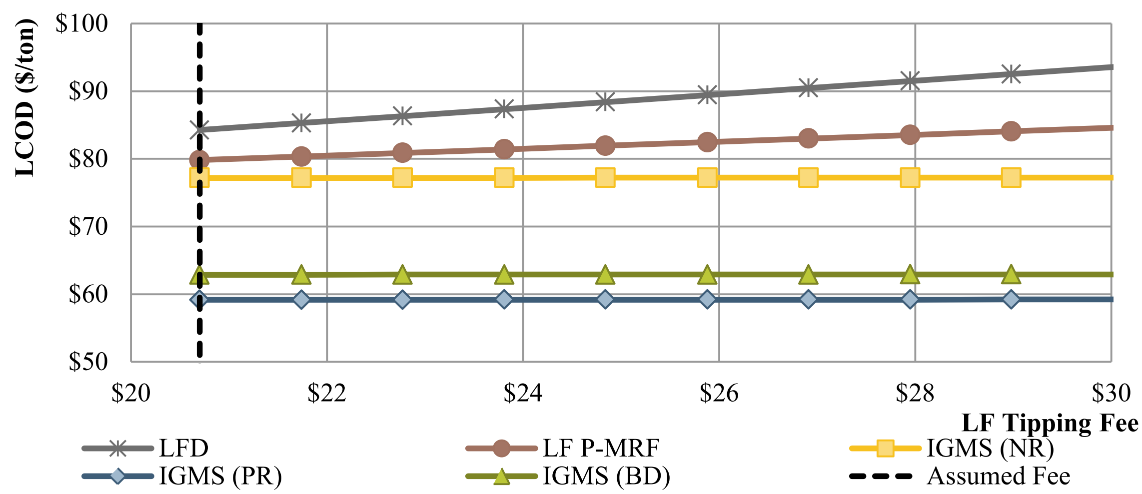



Figure 38. Sensitivity analysis of landfill tipping fee.

Figure 39 shows a sensitivity analysis on the contingency placed on technology implementation costs. Increased implementation costs of the dirty MRF in the LF P-MRF scenario has only a slight effect on the LCOD. Even if the cost of implementing the system is twice what was estimated for this analysis, the LCOD does not exceed the cost of LFD. With much higher investment costs for IGMS, the contingency has more influence on the LCOD of these systems. At a contingency increase of 75%, an additional \$8 million in capital costs, the LCOD for IGMS (NR) exceeds the cost of LFD. When selling electricity at renewable rates, even after doubling the cost of installing the MRF and gasification systems, these scenarios still operate at \$10 less per ton than LFD.

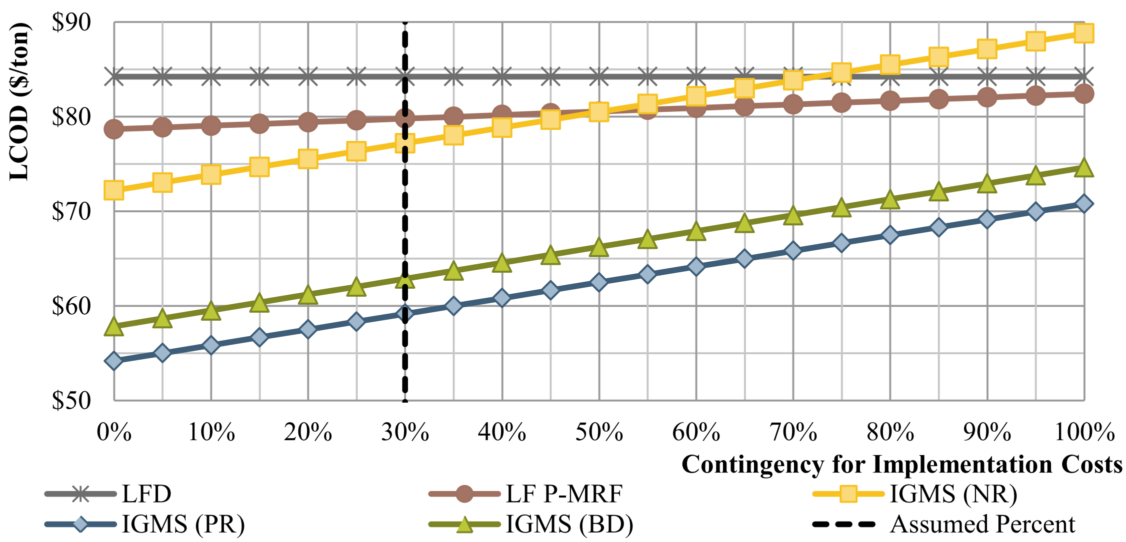



Figure 39. Sensitivity analysis of contingency placed on implementation costs.

Figure 40 shows the LCOD of the IGMS scenarios adjusting for the costs of consumables used in the gasification system (e.g. diesel fuel, lime, filters, water).

Figure 41 shows how the alternative management systems respond to increased maintenance and equipment replacement costs.  Again, in these sensitivity analyses large increases in operation and maintenance costs for IGMS (NR) can increase levelized costs above LF P-MRF and LFD LCOD.  In the scenarios where electricity is sold at a higher rates, the systems are equally reactive to these cost increases, but the LCOD remains below the other three management scenarios even if maintenance and equipment replacement costs are doubled.

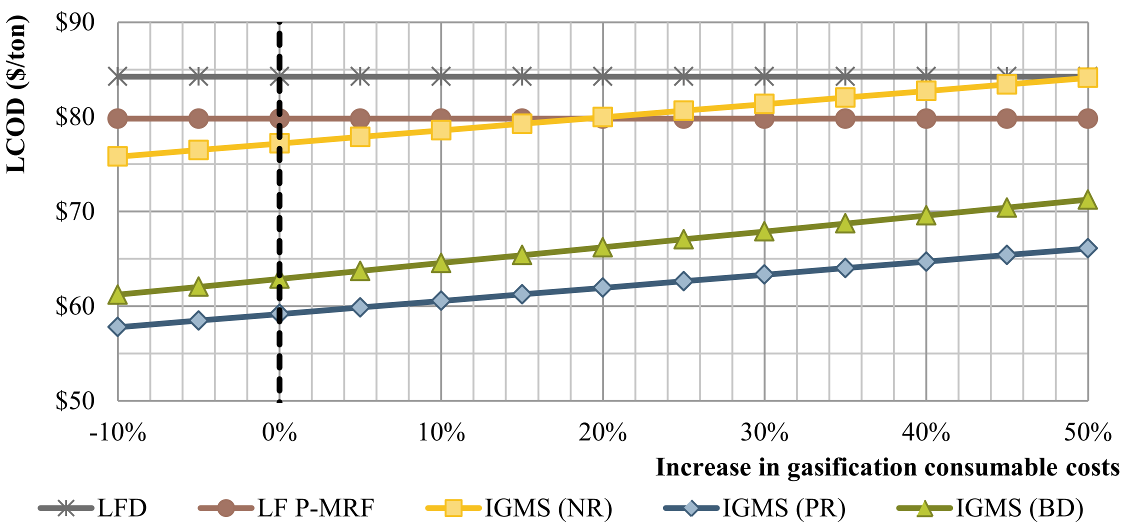



Figure 40.  Sensitivity analysis of gasification consumable costs.

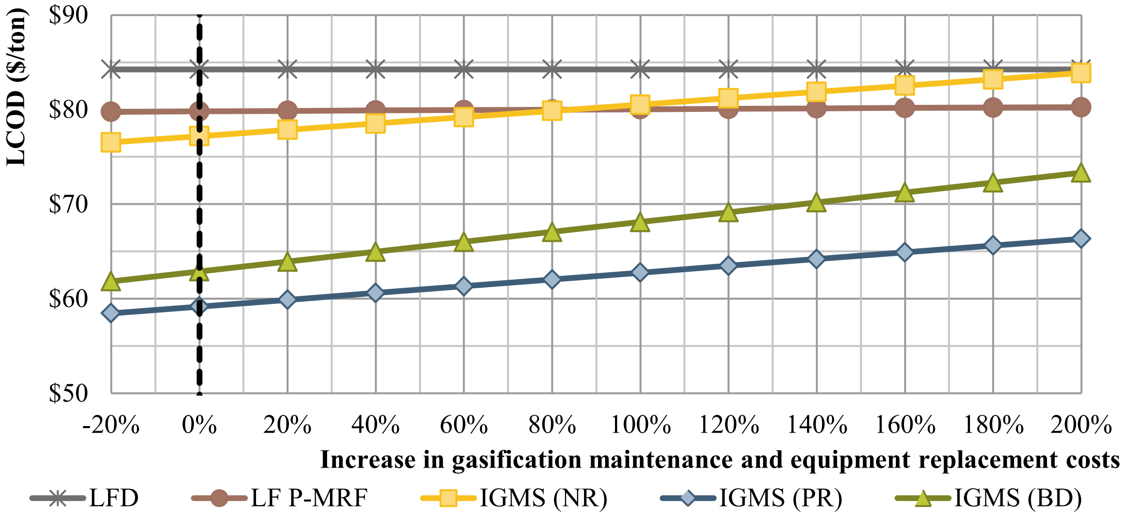



Figure 41. Sensitivity analysis of gasification maintenance and equipment replacement costs.

Fly ash produced by the AdaptiveARC system is a marketable product used in cement production. CEMEX is an international company that produces cement, aggregates, ready-mix concrete and other building materials and has an operation out of Sacramento, California. Interviews with individuals at this branch identified that CEMEX does purchase fly ash, but were unable to disclose a purchasing price. Transporting ash to Sacramento would cost approximately $54 per ton. From the annual 28,144 tons of RDF the ce25 systems would produce approximately 1,400 tons of fly ash. Due to the lack of information about fly ash revenue, the cost of transportation and revenues from ash sales were assumed net zero in the LCC analysis. The sensitivity analysis on of the sale price of ash in Figure 42 shows that costs of ash diversion has only a minor effect the economics of the IGMS scenarios.

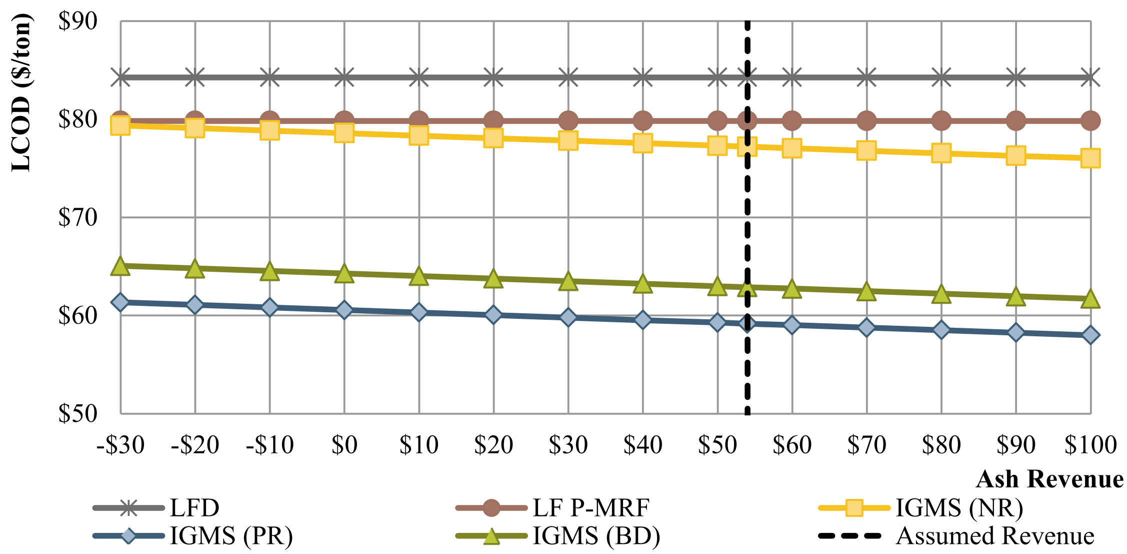



Figure 42. Sensitivity analysis on revenues from fly ash produced by gasifier.

In almost all of these sensitivity analyses, the alternative waste management systems operated at a lower cost than landfill disposal. Yet, the increased diversity of system costs and revenues can create more variability in the cost of waste management. These systems have increased variability, because they do not operate at a fixed rate like the landfill tipping fee. However, introducing more sources of cost and revenues gives HWMA more flexibility and control over managing solid waste. Operation of the LF P-MRF and IGMS could be adjusted in response to changing prices more easily than the LFD system.

Adapting a LF P-MRF management system is a good short-term solution to reducing the cost of MSW management. This system has a relatively low investment requirement, which is quickly recovered by the current HWMA tipping fee and by additional revenues from recycling. Operation of MRFs are highly documented and system costs would be rather predicable. Yet if diesel fuel prices continues to increase at the current rate, within 10 years the costs of operating this management system would need to be passed on to ratepayers with a tipping fee that increases above the rate of inflation to cover the higher costs of transportation.

Integrating gasification locally has the benefit of decreasing transportation requirements, increasing local industry thereby creating jobs, producing electricity, and providing additional revenue streams from MSW. Even with these benefits, installing a gasification system introduces some risk. The gasification technology is still evolving. Plasma arc gasification has been shown to be highly promising in that it has lower feedstock restrictions than the other forms of gasification, achieves higher energy efficiencies, and greater environmental performance (Arena, 2012). Long-term operational performance of plasma arc gasification is not yet available since the first commercial facilities were only installed in the last ten years. General operations and maintenance costs for gasification are not yet well documented. Policy and permitting for these facilities in California are also under development. This could lead to an increased cost of implementation, and introduces uncertainty about how these systems will be classified over time as a form of waste management, and as a renewable electricity generator. Even with these uncertainties, IGMS, especially with renewable energy classification, can greatly lower the cost of waste management in Humboldt County.

# CHAPTER 8. DISCUSSION OF RESULTS

Results from the feasibility analysis indicate that increased diversion of waste and energy recovery from RDF using gasification is a viable alternative for Humboldt County. An integrated gasification management system would enable the Humboldt community to achieve the following:

- reduce the environmental impact from landfilling MSW by reducing GHG emissions by more than 60%;
- provide an affordable waste disposal for the Humboldt community, by reducing the cost of waste disposal by 5% to 30%; and
- support of local and state initiatives for waste reduction and diversion by lowering the waste generate rate to 1.15 PPD and reducing landfill disposal to up to 99% of MSW.

Using a solid waste material recovery facility without an energy recovery system can reduce the amount of waste disposed at landfills by up to 60%. As seen Figure 43, decreasing the amount of waste disposed at landfills can reduce the GHG emissions associated with waste disposal by 67% . The LF P-MRF scenario also reduces lifecycle costs of waste management by $4.5 million compared to landfilling all MSW.

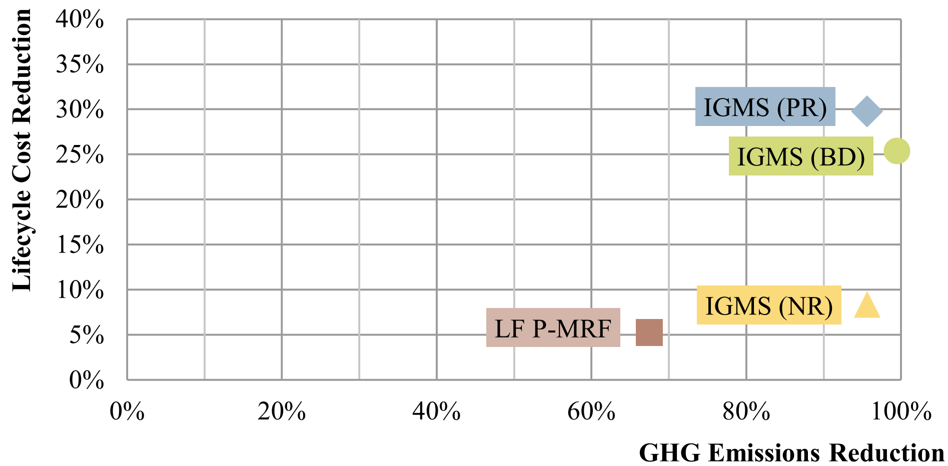



Figure 43. Greenhouse gas emissions and lifecycle cost reductions of alternative management scenarios relative to landfill disposal of MSW. The different scenarios are: LF P-MRF for landfill disposal of only post-material recovery facility residual wastes after diversion of recoverable materials and IGMS for an integrated gasification management system that performs energy recovery from residual waste and again uses a MRF for diversion of recoverable materials. The alternate energy classifications are represented by: (NR) for non-renewable energy classification, (PR) for pro-rated renewable energy classification, and (BD) for 100% renewable energy classification by operating on 100% biodiesel.

Alternatively, using a local gasification system to process residual wastes and diverting recoverable waste with a MRF has even greater environmental and economic advantages, as seen in Figure 43. By offsetting demand from the Humboldt Bay Power Plant with electricity produced from the gasification system, this integrated waste management system is considered close to carbon neutral.

The plasma arc gasification system has a high cost of implementation, but is able to recover this investment within a 20 year lifecycle and reduce the cost of solid waste management. Without renewable status and selling the electricity to the grid at a wholesale price, as seen in IGMS (NR) scenario, reduces the lifecycle cost of waste management compared to landfill disposal by $7 million. Receiving renewable energy classification and prorating the electricity from a gasification system operating on conventional diesel fuel, demonstrated in the IGMS (PR) scenario, provides the most economical option. This scenario is able to reduce the lifecycle costs of waste management by $25 million compared to continued landfill disposal of MSW.

The next sections will provide key recommendations or findings in the areas of environmental impact, system implementation, benefits and risks to HWMA and the Humboldt community. The final section in this chapter provides recommendations for improvements and variations to the proposed IGMS system.

## 8.1. Discussion of Key Findings

*This study recommends using a higher level of pre-processing than is required for feedstock compatibility with gasification.* The alternative waste management systems proposed by this is study were designed using the U.S. EPA's hierarchy of management methods as a guide for reducing the environmental impact of waste disposal. It is widely accepted that material recovery has a much lower impact that any other disposal method, and was prioritized in the design of these alternative waste management systems (Bohn, 2010; Morris, 1996; Villanueva & Wenzel, 2007). This is primarily due to secondary environmental benefits of material recovery including reduced manufacturing of raw materials and offset use of soil amendments. Diverting hazardous waste, like batteries and electronic wastes, reduces the toxicity of residual wastes. When performing energy recovery from RDF, these diversion efforts will reduce the concentration of volatized metals in flue gases, production of tars, and result in fewer air pollution emissions.

*Implementation of a solid waste MRF and gasification achieves verifiable GHG reductions that can support California's emissions reduction goals set by AB 32.* AB 32 calls for reducing emissions to 1990 levels by 2020 and further reducing emissions by 80% by 2050 (California Air Resources Board, 2013). The Climate Change Scoping Document identified that the waste sector accounts for 1% of California's GHG emissions. The recommended actions in the document include reducing methane emissions at landfills, increasing waste diversion, and directing waste management planning towards zero-waste, all actions captured in an IGMS (California Air Resources Board, 2008).

Established frameworks like the Climate Action Reserve protocol for accounting emissions from landfilling waste make emission reductions from alternative waste management systems verifiable, and possibly eligible to be traded in the carbon market as part of the California Cap-and-Trade Program. The first auction for credits successfully opened in November of 2012 at an average price of \$13.75 per $tCO_2e$, with prices ranging from \$91.13 to \$10.00. The allowances purchased were equivalent to 23 million $tCO_2e$ emissions; 97% of which purchased by compliance entities that are major sources of GHG emissions in the state such as refineries, power plants, industrial facilities, and producers of transportation fuels (CA EPA Air Resources Board, 2012). Over time, this market will be extended to more entities.

At this time, carbon regulation only applies to larger emitters like heavy industry, but smaller emitters will be included in the next compliance period in 2015 (California Air Resources Board, 2011). As an electrical generation source, the gasification system would be considered a small emitter in California's cap-and-trade system. The full implications of participating in the cap-and-trade program are not covered in this feasibility analysis, but if regulated, avoided emissions could potentially provide another source of revenue for HWMA.

*A material recovery facility greatly reduces disposal rates and meets State waste reduction goals.* Continuing with the current waste management system will make it difficult for HWMA to meet the diversion goal set by AB 341 of 75% diversion by 2030 and is one of the drivers of HWMA's development of a new strategic plan. Centralized sorting with a solid waste MRF would greatly support source separation efforts and possibly achieve 65% diversion of solid waste coming through HWMA, reducing waste disposal to 1.15 pounds per person day.

Minimum disposal tonnage requirements set by Dry Creek and Anderson Landfill could become a barrier to increased diversion. While there is currently not a minimum tonnage clause, this is something HWMA should avoid as they start negotiations for contract renewals.

*Electricity produced from residual waste could provide a low impact source of local electricity that could possibly contribute to California's RPS.* Gasification of RDF could provide up to 3.1 MW of local generation capacity. Annual electrical production from RDF would meet 2% of the county's demand, equivalent to powering 1,800 households.[46]

Compared to fossil fuels, electricity from RDF has a lower environmental impact from direct emissions production. This impact is even lower considering the avoided landfill gas production from this waste. Carbon dioxide emissions produced from biogenic wastes when converted by advanced thermal technologies are considered balanced by offset factors related in their carbon cycle by the "Accounting Framework for Biogenic Carbon Dioxide Emissions" created by the U.S. EPA (U.S. Environmental Protection Agency, 2011). Therefore, these emissions do not contribute to increasing the concentration of GHG in the atmosphere. Because RDF can contain products produced from fossil fuels, which are commonly plastics, not all the emissions are carbon neutral. Accounting for only the non-biogenic portion makes this gasification system operates at a much lower carbon intensity than coal per unit of electricity and slightly lower than electricity from the Humboldt Bay Generating Station when co-firing biodiesel instead of conventional diesel fuel as seen in Figure 44.

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[46] This is assuming an average household has an annual energy use of 6,456 kWh and is not engaging in indoor gardening (Pacific Gas and Electric Company, 2013b).

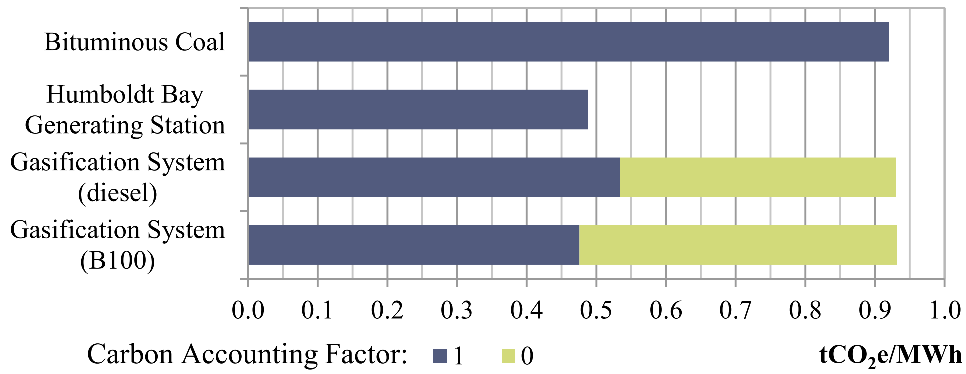


Figure 44. Carbon intensity of electricity from different sources. The plasma arc gasification system is shown co-firing diesel fuel as well as biodiesel fuel. Data sources: (U.S. Energy Information Administration, 2013c; U.S. Environmental Protection Agency, 2011)

There is still a lot of discussion surrounding whether MSW should be classified as a renewable resource. Some states do include electricity production from MSW in their renewable energy portfolios considering it a "naturally replenishing source". Other states focus on the presence of non-biogenic products in MSW, which make up most of the non-recoverable waste and therefore do not consider this electricity to be renewable. Biogenic waste in the U.S. comprised 63% of the waste stream by mass in 2005, but that proportion is slowly declining. Conversely, due to the presence of manufactured goods, the energy available in solid waste is increasing (Energy Information Administration, 2007).

California has stated technical, diversion, and performance requirements for renewable eligibility of electricity from gasification systems. Unfortunately, these technical and performance requirements are not yet well defined and have sent mixed signals to planning groups. The lack of clear regulations, based on actual environmental performance of gasification systems, creates a considerable barrier to developing waste as an energy resource.

Waste gasification offers an attractive renewable profile in that it can provide base load power and from a resource that is prevalent and occurs close to areas of demand. Intermittency of renewable energy sources provides a challenge to increasing the renewable portfolio standard and long distance transmission is costly and sustains efficiency losses. The cost of implementing the AdaptiveARC system is comparable to the capacity costs of implementing other emerging renewable energy technologies shown in Figure 45. An advantage of gasification over these other technologies is that the feedstock provides a secondary revenue source.

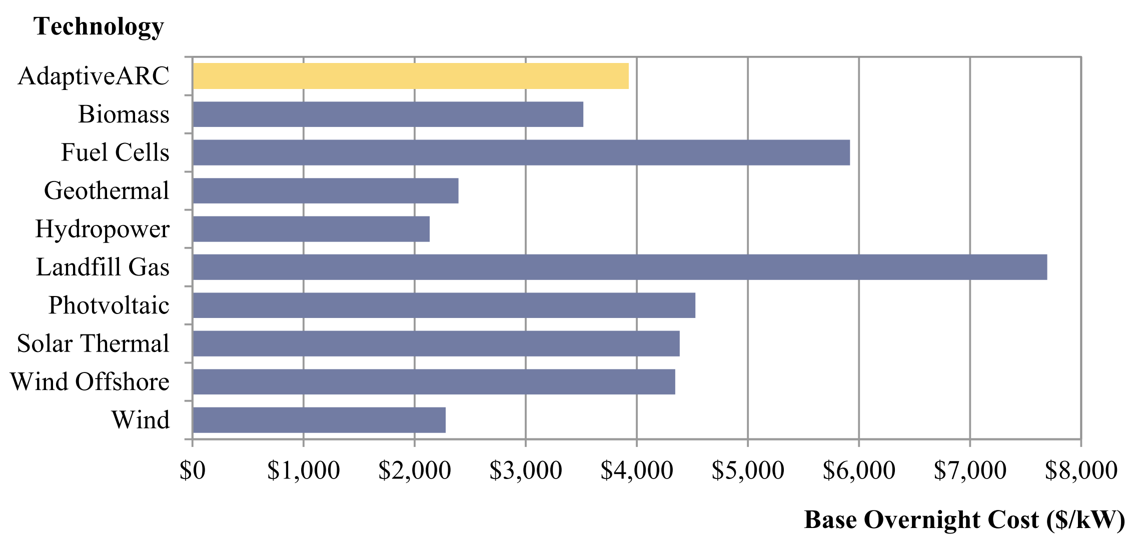


Figure 45. Comparison of capacity costs for implementing renewable energy technologies. Overnight costs refers to project capital costs without accounting for financing costs or escalation and is only used as a metric to compare feasibility. Data source: (U.S. Energy Information Administration, 2012c)

*More third-party testing of emissions and pollution data needs to be made available on gasification technologies.* A foremost concern of the public will be air pollutants produced by thermal conversion of RDF. Emissions from combustion of syngas from gasification systems have been shown to reliably meet stringent U.S. and international environmental performance standards. Advances in pollution control in gasification systems have been proven highly effective in pyrolysis, gasification, and plasma assisted gasification systems (Engineering-Center for Environmental Research and Technology, 2009; Youngs, 2011). Still, measured emissions from gasification of Humboldt's residual waste would be valuable information for identifying preprocessing improvements for RDF. AdaptiveARC is currently undergoing emission testing in California and expects to be able to release a report in 2013 (Damore, 2012).

*Advanced management technologies introduces cost variability but also system management flexibility.* The ability of landfills to offer a stable tipping fee can be convenient to municipalities providing waste management, who are required to maintain a stable service fee. In this situation, HWMA actually pays more per ton for transportation on waste than the tipping fee. As such, changes in fuel costs affect a larger proportion of HWMA's costs.

Separating waste and performing energy recovery from residual diversifies cost sources and produces additional revenues to the MSW management. With these systems, there will be inevitable variability in cash flows caused by market pricing trends and larger cost events, such as major equipment replacements. Because the management costs of the proposed advanced technology systems have more input variables, variation of individual line item costs has less impact on overall management costs compared to the continued landfill disposal system as demonstrated by the sensitivity analyses. The implementation of a solid waste MRF will give HWMA more control over waste management by providing the ability to customize waste streams. Ability to responsively change waste materials flows to market conditions or waste content could be a way to further stabilize waste management costs.

*Gaining community support for gasification early in the planning process will be important to the successful implementation of this project.* As a new technology, the general public typically does not differentiate between gasification and incineration. The confusion between of these two technologies could cause people to associate gasification with the pre-existing unfavorable reputation of incineration. Providing the community with more information about the technology and the risks and benefit it offers will be important to gaining support for the project.

A gasification system would localize some of the impacts of waste disposal, but will also offset local impacts of electricity production. Emissions produced from landfill disposal currently occur over 180 miles away. Although some pollutants are produced from the gasification systems, these technologies able to meet stringent environmental standards. Aside from emissions, increased local waste processing can result in other impacts such as odor, litter, and aesthetic appeal.

Active support from the community could also increase system performance. Practices like increased source diversion, separating mixed material products, or implementing a system of source separation of food waste would assist in higher levels of recovery and increase system efficiencies and possibly reduce system-operating costs.

*Localized waste disposal supports the local community and economy.* As an integrated system, a dirty MRF and local gasification system produce revenue streams that can supplement the cost of waste disposal. The associated savings can be passed on to the community in the form of lower disposal fees. These systems could also potentially provide 35 local green-collar jobs as well as introduce a new waste disposal industry to the county. These activities could retain more than $2 million annually of ratepayer's money in Humboldt County.

*Localized waste disposal options also provide autonomy for Humboldt County with waste disposal services and local energy production.* Currently HWMA contracts with two landfills in case one of the two major roadways out of the county becomes blocked. Increased local waste disposal in the form of composting, aerobic digestion, or gasification all reduce dependence on transportation of materials out of the county. In the case of emergencies, HWMA would have a source of electricity and a way to dispose of waste.

## 8.2. Recommendations for System Improvements

*Installing the IGMS in stages would distribute implementation costs and avoid installing unnecessary excess capacity.* Both the solid waste MRF and a gasification system could be installed in stages. Advanced planning for installing the MRF in stages allows for flexibility to be designed into the system. If the base equipment for a solid waste MRF was initially installed, such as conveyers and basic sorting equipment, over time HWMA could continue to add specialized equipment as needed. By installing and operating the solid waste MRF before implementing gasification, valuable data would be collected about material flows composition and volume of RDF that will better identify the characteristics desired in a gasification system.

The AdaptiveARC system and most other gasification systems are modular in design and have a processing range of 10 to 100 tpd with an average gasifier capacity of 50 tpd. A unique feature of the Adaptive ARC system is that is has a very low infrastructure requirement, since their unit is designed to be portable, making it highly suitable for scaling. While most systems are not self-contained like AdaptiveARC, it is possible to affordably add capacity over time as needed.

*There is the possibility of including other expensive and problematic waste streams as feedstock for gasification.* Wastes like municipal sludge from wastewater treatment, flammable liquids, and untreated medical wastes are disposed of at a high cost to the county and community (Whitener, 2012). Accepting these types of feedstocks would provide affordable and local disposal options for these waste streams. Another feedstock tested in the AdaptiveARC system is landfill gas and mined landfill waste. Post-landfilled materials provide an interesting opportunity, in that spaces used as landfills could be reclaimed and returned to their original state or repurposed for alternative uses (Frändegård, Krook, Svensson, & Eklund, 2012; Hogland, Marques, & Nimmermark, 2004).

*Investigate alternative technologies for utilizing syngas from gasification.* In addition to the use of biodiesel as described previously, there are several options for reducing the diesel demand of the IGMS. It may be possible for the AdaptiveARC system to use a generator that co-fires natural gas with syngas for electricity production. Caterpillar is trying to meet the demand for mid-sized engines that can operate on low energy density fuels like syngas or biogas (Williams, 2012). This option would still require an external fuel source, but could reduce operating costs since natural gas is currently less expensive than diesel fuel.

Another option for utilizing syngas is a Fischer-Tropsch process to create liquid fuels. In an effort to develop a strategic plan for energy security in Humboldt County, the Schatz Energy Research Center and the Redwood Coast Energy Authority prepared a report assessing community goals, resource availability, and detailed energy models to identify feasible plans for developing local energy sources. While there were many local renewable electricity sources identified, transportation fuels make up one third of the county's energy demand and very few local liquid fuel sources exist (Schatz Energy Research Center, 2013). Synthetic diesel from syngas has a higher octane level than petroleum fuels, and without the presence of sulfurs, burns cleaner (Zoellick et al., 2005). As a premium quality fuel and with the increasing price of liquid fuels, this option for utilizing syngas could possibly be more economical than producing electricity.

AdaptiveARC is already actively developing this option for their system and expects it to be available in the next few years (Damore, 2012).

# CHAPTER 9. CONCLUSION

The Humboldt Waste Management Authority (HWMA) provides waste disposal services to the majority of Humboldt County. Since the closing of the Cummings Road Landfill in 2000, municipal solid waste is hauled an average of 180 miles to landfills out of the county. This disposal method has become increasingly more expensive with rising fuel cost resulting in waste disposal fees that are much greater than the national average. Furthermore, landfilling disposal produces high levels of methane, which is a potent GHG. From the waste received by HWMA in a single day, 80 $tCO_2e$ of greenhouse gas emissions will be produced from transporting waste and landfill gas production.

This thesis investigates the feasibility of an integrated waste management system that performs energy recovery from residual waste free of household hazardous and universal wastes, recyclables and organic materials. Gasification is a non-combustion thermal process that converts unrecoverable waste to marketable solids and an energy rich fuel gas, syngas, that can be used to produce electricity and liquid biofuels. Still considered a young technology, the objective of this study was to determine the feasibility of gasification systems currently available on the market.

The AdaptiveARC plasma arc gasification system was selected for analysis, out of five companies, each providing a different type of gasification technology. Pairing this energy recovery with central sorting of MSW using a solid waste MRF would provide a waste management system that fully utilizes the resources in waste, as shown in

Figure 46. This feasibility analysis has shown that gasification of post-sorted residual provides a waste management system with a lower environmental impact and at a lower cost than landfill disposal.


Figure 46. A better use of solid waste. An integrated waste management system with local gasification has the potential to recover valuable raw materials and energy. An IGMS would convert one ton of MSW into 450 pounds of reusable raw materials, 350 pounds of compost, and 293 kWh of electricity, and 41 pounds of construction aggregate, while reducing costs to ratepayers and the environmental impact of waste disposal.

Characteristics of Humboldt County including: remote setting, high tipping fees, a central waste management authority, low MSW throughputs, a food waste diversion effort and planned anaerobic digestion system, a current waste characterization study, demand for local energy sources, and community interest in environmental protection result in an unique, even ideal, setting for implementing an integrated gasification management system. As a community that prides itself as a leader in promoting sustainability, gasification is an opportunity to demonstrate innovate waste management that supports environmental protection, the local economy, and benefits the community.

In the bigger picture, gasification is getting a lot of publicity as the future of waste disposal and many of these claims seem to be too good to be true. The uncertainties of deploying gasification, including its renewable energy status and long-term operation and maintenance costs, have proved too uncertain for many municipalities who are used to contracted fees and one-stop-shops for disposal. Gasification is perceived to be an expensive process to implement and operate, but is able to provide multiple environmental services, many of which are not easily quantified, such as: avoided land use and fixation of pollutants that reduces risk of soil and water contamination. Even with all that gasification has to the offer, the primary waste management question should be: how can waste be less wasteful? It will be the collaborative effort of manufacturers, consumers, waste generators, and innovators thinking outside the landfill that will answer this question.

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# APPENDIX A: THERMAL CONVERSION REQUIREMENTS TO MEET THE CALIFORNIA RENEWABLE PORTFOLIO STANDARD

This appendix contains excerpts from the California Public Resources Code and Renewable Portfolio Commission Guidebook about the Renewable Portfolio Standards eligibility of electricity produced from MSW by a gasification system.

## California Public Resources Code, Portion of SECTION 40100-40201

40117. "Gasification" means a technology that uses a noncombustion thermal process to convert solid waste to a clean burning fuel for the purpose of generating electricity, and that, at minimum, meets all of the following criteria:

a) The technology does not use air or oxygen in the conversion process, except ambient air to maintain temperature control.
b) The technology produces no discharges of air contaminants or emissions, including greenhouse gases, as defined in subdivision (g) of Section 38505 of the Health and Safety Code.
c) The technology produces no discharges to surface or groundwaters of the state.
d) The technology produces no hazardous waste.
e) To the maximum extent feasible, the technology removes all recyclable materials and marketable green waste compostable materials from the solid waste stream prior to the conversion process and the owner or operator of the facility certifies that those materials will be recycled or composted.

f) The facility where the technology is used is in compliance with all applicable laws, regulations, and ordinances.

g) The facility certifies to the board that any local agency sending solid waste to the facility is in compliance with this division and has reduced, recycled, or composted solid waste to the maximum extent feasible, and the board makes a finding that the local agency has diverted at least 30% of all solid waste through source reduction, recycling, and composting.

**Renewable Portfolio Standard Eligibility**

(Commission Guidebook, May 2012) pg. 29-30

*Municipal Solid Waste*

Electrical generation produced by a facility that uses municipal solid waste (MSW) as defined in the Overall Program Guidebook is eligible for the RPS. Two types of MSW facilities are eligible:

1. Municipal Solid Waste Combustion Facilities: A facility that directly combusts MSW to produce electricity is eligible for the RPS only if it is located in Stanislaus County and was operational before September 26, 1996.[45] An applicant for a combustion facility must submit documentation to the Energy Commission demonstrating that the facility meets these requirements.
2. Municipal Solid Waste Conversion Facilities: A facility is eligible for the RPS if 1) it uses a two-step process to create energy whereby in the first step, gasification[46] conversion, a noncombustion thermal process that consumes no excess oxygen, is used to convert MSW into a clean-burning gaseous or liquid fuel, and then in the second step this clean-burning fuel is used to generate electricity, and 2) the facility and conversion

technology meet all of the following applicable criteria in accordance with Public Resources Code Section 25741, Subdivision (b)(3):

a. The technology does not use air or oxygen in the conversion process, except ambient air to maintain temperature control.
b. The technology produces no discharges of air contaminants or emissions, including greenhouse gases as defined in Section 38505 of the Health and Safety Code.
c. The technology produces no discharges to surface or groundwaters of the state.
d. The technology produces no hazardous wastes.
e. To the maximum extent feasible, the technology removes all recyclable materials and marketable green waste compostable materials from the solid waste stream before the conversion process, and the owner or operator of the facility certifies that those materials will be recycled or composted.
f. The facility at which the technology is used complies with all applicable laws, regulations, and ordinances.
g. The technology meets any other conditions established by the Energy Commission.
h. The facility certifies that any local agency sending solid waste to the facility diverted at least 30 percent of all solid waste it collects through solid waste reduction, recycling, and composting.

In addition to the certification or precertification application, applicants for MSW facilities must complete the supplemental application form for biopower, CEC-RPS-1:S1, found in Appendix B, and provide the additional required information described below.

45 Public Utilities Code section 399.12, Subdivision (e)(2).

46 This process is referred to as “gasification” in Public Resources Code Section 40117, as implemented by the California Department of Resources Recycling and Recovery (CalRecycle). The requirements of Section 40117 mirror the requirements of Public Resources Code Section 25741, Subdivision (b), as applicable to municipal solid waste conversion.

# APPENDIX B: EVALUATION AND TECHNOLOGY SCREENINGS

This appendix describes evaluation criteria and qualifying technologies from reports prepared for the County of Santa Barbara in 2008 and the County of Los Angeles in 2005.

Table B.1 Matrix of technologies that met evaluation criteria in technology reviews for different counties.

| | Adaptive ARC | ENTECH Renewable Energy Solutions | IES International Environmental Solutions | IWT Interstate Waste Technology | Plasco Energy Group |
|---|---|---|---|---|---|
| County of Santa Barbara 2008 | x* | x | x | x | x |
| County of Los Angeles 2005 | | x | x | x | |

*Submitted with AdaptiveNRG

**Evaluation Criteria for City and County of Santa Barbara**[47]

- Any considered CT must be capable of processing a minimum of 100,000 tons per year (tpy) of MSW during the first operating year of the project, and must be capable of increasing capacity up to 220,000 tpy within 10 years of the first operating year of the project.
- Any considered CT must be capable of operating for a minimum of 20 years.
- Any considered CT must be compatible with local solid waste management programs, including recycling programs.

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47 Description of technology supplier ranking criteria produced for the City and County of Santa Barbara (Alternative Resources, Inc., 2008b).

- Any considered CT must be capable of diverting at least 60% by weight of the MSW received for processing from landfill disposal.
- Any considered CT must have a projected tip fee that limits financial impact to affected ratepayers (i.e., no more than 10% beyond the price the ratepayer would expect for other alternatives).
- Any considered CT must produce end products that have probable, identifiable or existing markets (including electricity and/or fuel products).
- Any considered CT must conform to California environmental standards, and must limit and/or mitigate environmental impacts of landfilling MSW.
- Any considered CT must have been demonstrated at a minimum of one facility of similar size or with a minimum unit size of 50 tpd (tpd), and shall have been in operation for at least six months (as of February 29, 2008) processing MSW or similar feedstock.
- Any considered CT must have a project team that has experience designing, building and operating a solid waste management facility, either individually or as a team.
- The project developer must have bonding ability equal to the estimated cost of facility design and construction, and, during operation, equal to the estimated annual operating cost; must not be in bankruptcy; and must provide a financing plan that reasonably demonstrates that it can offer private project financing, if required.
- The project developer must not be debarred from contracting in California.

**Evaluation Criteria for the City and County of Los Angeles**[48]

- Waste Suitability: Suppliers who have operating experience with MRF residuals or MSW will be ranked higher than suppliers who have processed other types of feedstocks similar to MRF residuals, such as biomass (e.g., green waste), plastics and tires. Lack of MSW processing experience introduces potential operational risks.
- Need for Equipment Scaling to 100 TPD: When evaluating suppliers for a demonstration facility, many suppliers will have operating experience with systems far smaller than 100 TPD. Increasing throughput can be accomplished by designing larger modules or adding more modules. Designing larger modules introduces scaling risk.
- Marketability of Conversion Products: We have defined a conversion facility to have the ability to convert MRF residuals to marketable products. Suppliers with products (e.g., electricity, ethanol, metals, compost, etc) that have existing strong market will score higher than those without market.
- Engineering the Complete System: Some suppliers have expertise in only one technical area (e.g., preprocessing, conversion, or power production), while others have designed and built complete systems. Lack of expertise in one or more areas introduces design risks.
- Existing Operational Experience: Suppliers with more operating experience will be ranked higher than those with less experience. More experience should result in smaller development risk.

[48] Descriptions of technology supplier ranking criteria produced for Los Angeles County. (Predpall, Ruiz, Skye, Jauregui, & URS Corporation, 2005)

- Economics: The supplier must provide costs that are within reasonable ranges, and provide sufficient backup to understand the costs. Similarly, suppliers must demonstrate an understanding of product marketing. Suppliers that provide clear and reasonable costs and revenue projections will be rated higher.
- Landfill Diversion: Suppliers who produce more marketable products, and thus less residuals, will be ranked higher. Larger amounts of residuals may lead to higher costs, and requires more landfill capacity.
- Supplier Credibility: Suppliers must have organizations with the technical and financial resources to carry out design, construction and commissioning of a conversion facility. Suppliers with more resources will be rated higher (Predpall et al., 2005).

# APPENDIX C: WASTE THERMAL CONVERSION TECHNOLOGY REQUEST FOR INFORMATION

## Request for Information: Waste Thermal Conversion Technology for Application in Humboldt County

The purpose of this Request for Information is to identify a commercially available thermal conversion technology with energy recovery suitable for processing 28,000 to 33,000 tons per year of residual separated from Humboldt County solid waste stream.

Humboldt County is an isolated community in Northern California with a population of 135,000. In 1998, the Humboldt Waste Management Authority (HWMA) was formed as a California Joint Powers Authority by five incorporated cities and the County of Humboldt. The HWMA manages the majority of the county's solid waste stream, approximately 70,000 tons per year, as well as an integrated waste management program, a yard waste compost facility, a permanent household hazardous waste collection facility, recyclable materials collection, and is currently developing a food waste diversion program. HWMA is interested in a viable method for processing the residual waste that cannot be diverted through these programs.

The following information is requested in order to evaluate landfill diversion opportunities available:

- A list of materials targeted as the residual waste stream is provided in Appendix A of the RFI (Appendix F in this document). Provide a list of materials from this characterization that could be processed by your technology. Use tonnages that can be processed by your technology to answer the questions that follow. Also, describe any additional required preprocessing of the feedstock.
- Provide a technical description of you technology.
- Provide a flow diagram of your technology with your recommended configuration for this quantity of waste. What would be the footprint of this system (sq.ft.)?
- Is your technology modular or flexible in its design? If so, describe how this system is able to accommodate waste that exceeds the original design parameters.
- List materials from the following commodity stream that are compatible with your system: tires, flammable liquids, dry cell alkaline batteries, medical wastes and sharps, liquid and solids, toxic residential wastes, or biosolids sludge.
- Does your technology include an electrical generation component? If so, what type of generator, what is its nameplate generation and efficiency rating? In the case of a steam power turbine what is the water demand (gal/kWh)?
- Based on the feedstock mix appropriate for your technology, what is the expected electrical generation output (kWh/ton)?
- Please describe the composition and generation rate of the residual produced by your technology. If marketable, describe the market, and the estimated annual revenue. If unmarketable, what is the recommended disposal method?

- What is the energy demand of the entire system, both in terms of natural gas and electricity (therms and kWh per ton)?
- Describe how your technology meets California Air Quality Board emission standards. If available, please provide third party evaluation of both exhaust air quality and greenhouse gas emissions.
- Provide capital and installation costs associated with your technology with an explanation of the major components as well as any expected duty or taxes.
- Provide estimated annual operating and maintenance costs and requirements, number of operators, and estimated life span of technology components.
- Provide a brief timeline for project implementation.
- Provide descriptions and references for up to three relevant demonstrations of your technology.

# APPENDIX D: MSW MATERIAL RECOVERY FACILITY REQUEST FOR INFORMATION

## Request for Information: MSW Material Recovery Facility for Humboldt County

Information about a solid waste material recovery facility is requested as part of an analysis of the application of thermal waste conversion technologies for the Humboldt Waste Management Authority, HWMA, who processes the waste for the majority of the county, about 70,000 tons annually. I am looking for a quote for a MSW MRF that could be sited on the current tip floor of HWMA. Due to our remote location, HWMA hauls waste over 100 miles for disposal, which is impractical and costly. This has HWMA very interested in diversion options, and as such is in the pilot phases of a county biodigester system. Currently HWMA is in the process of creating a Strategic Plan and this report will be a part of HWMA's reevaluation as they go through this process.

I am requesting a quote for a material recovery system that could accomplish the following:

- Can sort municipal solid waste
- Uses both mechanical and manual sorting
- Can fit within the Tip Floor building
- Sort waste into 4 streams of (1) single stream recycling of both containers and fibers (2) food waste and compostable materials (3) universal waste and electronic waste (4) residual waste that essentially everything else free of metals and glass

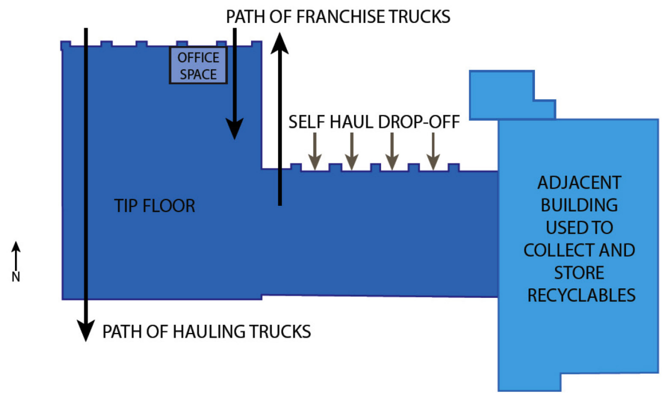
- Appropriate for our small community and diminishing waste stream currently 70,000 tpy (approximately 200 tpd) which decreased by 20% in the last 5 years

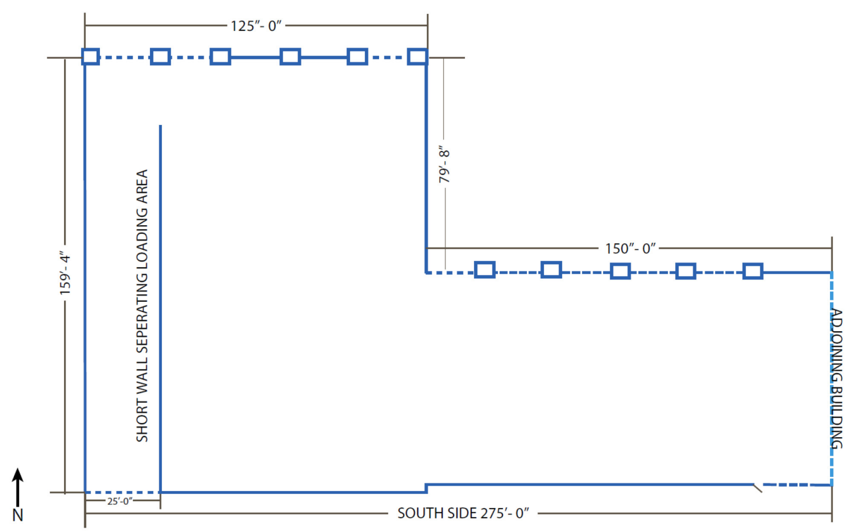
I am interested in:

- Equipment cost estimate
- Operation schedule and estimate of labor requirement for operation
- Estimate of maintenance costs
- Flow diagram of proposed MSW materials recovery facility
- If not too difficult to determine: what would be the approximate electrical demand of the facility?

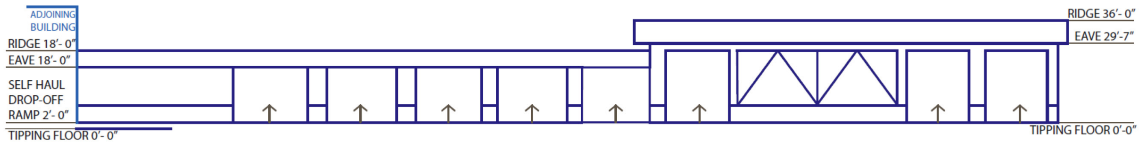
In this document I have also included the results of the Characterization Study for Humboldt County released this year and a diagram of the HWMA Tip Floor.

**Humboldt Waste Management Authority Transfer Facility: Tip Floor Layout**

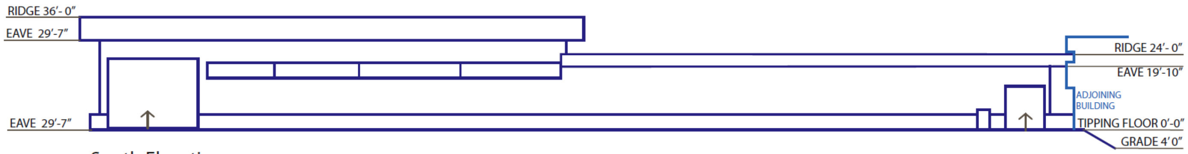


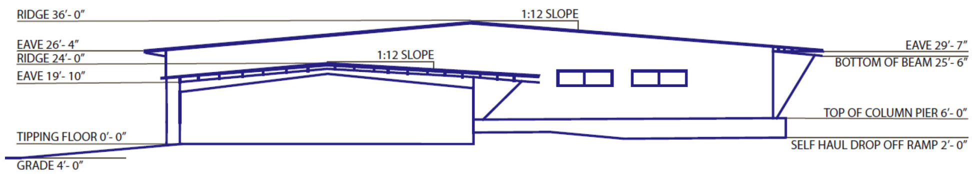

Tip Floor Floor Plan



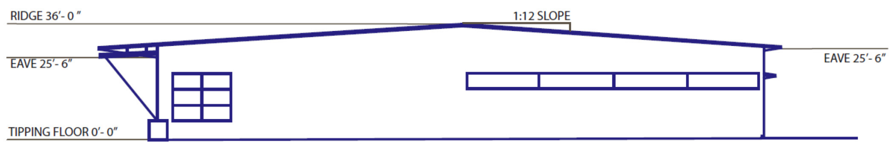

North Elevation




South Elevation




East Elevation




West Elevation

## APPENDIX E: ENTECH RFI RESPONSE SUMMARY

Entech provided a response the 'Request for Information: Waste thermal conversion technology for application in Humboldt County' recommending what they have named the WtGas system that uses pryolytic technology for low temperature gasification. They produce gasification units that can process 5 to 100 tpd. Their system accepts all the materials in the proposed RDF. The only preprocessing required is shredding.

In the system depicted on their website, feedstock enters the gasification chamber by an automated feed system. The waste materials are processed over a period of 16 to 24 hours in a low temperature-substoichiometric environment and undergo regular churning and stoking to ensure complete gasification. The produced syngas is directly fed into what they call a "Syn-Gas Burner". The primary components of the flue gases are carbon dioxide and water vapor. This system utilizes a low nitrogen oxide burner design that has a high destruction rate efficiency of organic pollutants such as volatile organic compounds and dioxins. The burner powers boilers to produce steam to generate electricity. Flue gases go through a final air quality control system. Entech reports that resulting emissions comply with stringent emission regulatory requirements and has over 160 gasifier units in operation worldwide (Entech-Renewable Energy Solutions Pty Ltd, 2012).

In the RFI response, Entech stated that the turbine/generator set and main transformer is sized to the amount of feedstock and is able to use any brand. The system requires little to no makeup water since the moisture from the feedstock is captured in the condenser. A 1,000 tpd plant can produce 36 MW of electricity or 78 MW of thermal a hour. The parasitic load is less that 10% and only requires supplemental natural gas for 18 hours during system startups. The system reduces feedstock to less than 3% inert ash.

A 5,000 ton a day facility would employ approximately 900 people for engineering and construction and take 28 to 30 months to construct. A 1,000 tpd plant would typically take 16 to 18 months to be up and running. When in operation, a 5,000 tpd plant would employ 500 people as operators, sorters, maintenance working and heavy machinery operators. Facilities operate seven days a week, 24 hours a day.

Entech also reports that Bio Energy Costa Rica (BECR), a partner of Entech, would finance this facility with no cost to the community. They would want at least a 10 year contract guaranteeing waste throughput and tipping fee with a small escalation clause, as well as contract for the sale of any energy byproducts. Entech provided no other details about costs of the system (Arca & Entech Renewable Energy Solutions, 2012).

# APPENDIX F: HUMBOLDT COUNTY COMPOSITION OF RDF

Table F.1 List of materials comprising RDF including estimated annual tonnage, energy density, and moisture content (Cascadia Consulting Group & HWMA, 2012; Kaplan et al., 2009; U.S. Environmental Protection Agency, 2011).

| Material | Proportion of MSW | Annual Tons | MMBtu/ dry ton | Moisture Content | MMBtu/ wet ton |
|---|---|---|---|---|---|
| Paper | 7.0% | 2,138 | | | |
| Waxed Corrugated Cardboard | 0.17% | 13.8 | 13.8 | 4% | 0.02 |
| Single-Use Paper Cups | 0.84% | 12.5 | 12.5 | 4% | 0.10 |
| Remainder/Composite Paper | 6.03% | 13.1 | 13.1 | 10% | 0.71 |
| Plastic | 23.0% | 6,998 | | | |
| Single-Use Expanded Polystyrene Food Service Items | 0.88% | 35.6 | 35.6 | 3% | 0.31 |
| Plastic Trash Bags | 4.12% | 20.5 | 20.5 | 2% | 0.00 |
| Plastic Grocery and Other Merchandise Bags | 0.83% | 20.5 | 20.5 | 2% | 0.83 |
| Non-Bag Commercial and Industrial Packaging Film | 0.85% | 20.5 | 20.5 | 2% | 0.17 |
| Film Products | 1.13% | 20.5 | 20.5 | 2% | 0.23 |
| Other Film | 6.31% | 20.5 | 20.5 | 2% | 1.27 |
| Other Non-Recyclable Rigid Plastic | 2.69% | 37.4 | 37.4 | 2% | 0.98 |
| Remainder/Composite Plastic | 6.23% | 18.3 | 18.3 | 8% | 1.05 |
| Glass | 0.8% | 241 | | | |
| Remainder/Composite Glass | 0.79% | 2.9 | 2.9 | 8% | 0.02 |
| Metal | 4.8% | 1,451 | | | |
| Remainder/Composite Metal | 4.78% | 2.9 | 2.9 | 8% | 0.13 |
| Other Organic | 42.0% | 12,771 | | | |
| Textiles | 10.71% | 15.5 | 15.5 | 2% | 1.63 |
| Carpet | 2.99% | 20.0 | 20.0 | 2% | 0.59 |
| Animal Carcasses | 0.09% | 7.12 | 7.12 | 70% | 0.002 |
| Remainder/Composite Organic | 28.26% | 7.7 | 7.7 | 59% | 0.88 |

(Table continued on next page)

| Material | Proportion of MSW | Annual Tons | MMBtu/ dry ton | Moisture Content | MMBtu/ wet ton |
|---|---|---|---|---|---|
| Inerts and Others | 16.5% | 5,014 | | | |
| Clean Engineered Wood | 1.67% | 13.3 | 13.3 | 35% | 0.14 |
| Other Wood Waste | 7.63% | 10.0 | 10.0 | 35% | 0.49 |
| Clean Gypsum Board | 0.22% | 0.4 | 0.4 | 0.3% | 0.00 |
| Painted/Demolition Gypsum Board | 2.96% | 0.4 | 0.4 | 0.3% | 0.01 |
| Remainder/Composite Inerts and Other | 4.03% | 8.5 | 8.5 | 33% | 0.23 |
| Special Waste | 5.8% | 1,715 | | | |
| Pharmaceuticals | 0.03% | 0.0 | 0.0 | 2% | 0.00 |
| Treated Medical Waste | 0.10% | 11.7 | 11.7 | 2% | 0.01 |
| Mattresses | 0.09% | 13.8 | 13.8 | 2% | 0.01 |
| Bulky Items | 4.38% | 13.8 | 13.8 | 2% | 0.59 |
| Remainder/Composite Special Waste | 0.59% | 11.7 | 11.7 | 8% | 0.06 |
| Mixed Residue | 0.59% | 11.7 | 11.7 | 27% | 0.05 |
| **Totals for Residual Derived Fuel** | **100%** | **30,391** | **12.8** | **25%** | **23.9%** |

## APPENDIX G: UNIT PRICING FOR COMPONENTS IN LCC

Table G.1 Cost and revenue assumptions used in the LCC model of the different waste management scenarios.

| Description | Unit Price | Source |
|---|---|---|
| AdaptiveARC 110 tpy system | $11,880,000 | Response to RFI (Damore & AdaptiveARC, Inc., 2012) |
| Installation of MRF | $ 3,560,000 | Estimate from responses to RFI (Atchison & CP Group of Companies, 2012; Harris & Sierra International Machinery, 2012) |
| Permitting site Development | $1,500,000 | Estimate based on costs reported by Bohn (Bohn, 2010) |
| Revenue from tipping fee | $62.84 per ton | HWMA average fee for 2012 FY (Humboldt Waste Management Authority, 2011) |
| Cost of landfill haul | $ 35.68 per ton | HWMA average fee for 2012 FY (Humboldt Waste Management Authority, 2011) |
| Cost of landfill fee | $ 20.70 per ton | HWMA average fee for 2012 FY (Humboldt Waste Management Authority, 2011) |
| Cost of Aerobic Digestion | $47.00 per ton | From levelized net LCC (Bohn, 2010) |
| Cost for Wes Green | $55.00 per ton | Costs for 2012 FY (Egerer, 2012c) |
| Cost for Dry Creek | $64.50 per ton | Average cost of hauling and service fee for Dry Creek Composting Facility 2012 (Egerer, 2012) |
| Cost for processing household hazardous and universal waste | $ 9.54 per ton | Average revenue from residential sources which account for 90% of tonnage (Sherman, 2012) |
| Revenue from scrap metal | $ 165 per ton | Average sale price for Arcata Scrap and Metal (Egerer, 2012; Egerer, 2012a; Recycling Business Assistance Center, 2012) |
| Revenue from corrugated cardboard | $ 100 per ton | Average sale price (Egerer, 2012c; Recycling Business Assistance Center, 2012) |
| Revenue from rigid plastics | $ 125 per ton | Average sale price (Egerer, 2012c; Recycling Business Assistance Center, 2012) |
| Revenue from mixed recycling | $11 per ton | From current contract with Solid Waste of Willits (Egerer, 2012) |
| Cost of electricity | $ 190 per MWh<br>$ 9,364 demand charge | HWMA 2011 average electrical pricing and demand charges for last year (Jacobson, 2012) |
| Cost of diesel fuel | $ 4.23 per gallon | Average cost of diesel in California from November 2011- November 2012 (U.S. Energy Information Administration, 2012b) |
| Cost of biodiesel | $ 5.18 per gallon | Average cost provided by Renner Petroleum (Galidy, 2012) |
| Revenue from wholesale electricity to grid | $39.06 per MWh | Average price of electricity on the California wholesale market from March 2012- 2013 (U.S. Energy Information Administration, 2012b) |
| Revenue from renewable electricity to grid | $104.31 per MWh | Average contracted price under PG&E renewable feed-in tariff scheme (Pacific Gas and Electric Company, 2013a) |

# APPENDIX H: LLC CALCULATIONS FOR INDIVIDUAL SYSTEM COMPONENTS

Costs and revenues used in the LCC model for each waste management scenario. Escalation rates were applied to an annual cash flow, then discounted to determine the discounted LCC over 20 years.

Table H.1 Treatment of costs and revenues for Landfill Disposal of all MSW

| Line Item Description | Escalation Rate | Year |
|---|---|---|
| Costs Sources | | |
| Landfill Transport Costs | Diesel Price Escalation | 1 through 20 |
| Landfill Tipping Fee | Fixed Rate | 1 through 20 |
| Revenue Sources | | |
| HWMA MSW Processing Tipping Fee | General Inflation | 1 through 20 |

Table H.2 Treatment of costs and revenues for Landfill disposal of post-MRF residual

| Line Item Description | Escalation Rate | Year |
|---|---|---|
| Costs Sources | | |
| Capital Costs<br>- Equipment<br>- Installation<br>- Permitting and Site Development<br>- 30% Contingency | None | 0 |
| Major Equipment Replacement<br>- Solid Waste MRF | General Inflation | 5, 10, 15 |
| Energy<br>- Electricity | Electricity Price Escalation | 1 through 20 |
| Wages<br>- Solid Waste MRF | General Inflation | 1 through 20 |
| Diversion and Landfill Transport Costs<br>- Arcata – green waste compost<br>- Ukiah – compost<br>- Willits – recycling<br>- Landfill – residual | Diesel Price Escalation | 1 through 20 |
| Tipping Fees<br>- Ukiah – food waste<br>- Landfill – inerts | Fixed rate | 1 through 20 |
| Anaerobic Digestion<br>- Food waste | General Inflation | 1 through 20 |
| Revenue Sources | | |
| Bulk Recycling Revenue | General Inflation | 1 through 20 |
| Mixed Recycling Revenue | Fixed rate | 1 through 20 |
| HWMA MSW Processing Tipping Fee | General Inflation | 1 through 20 |

Table H.3 Treatment of costs and revenues for IGMS (NR/PR/BD)

| Line Item Description | Price Escalation Rate | Year |
|---|---|---|
| **Cost Sources** | | |
| Capital Costs<br>- Equipment and Installation<br>- Permitting and Site Development<br>- 30% Contingency | None | 0 |
| Major Equipment Replacement<br>- Solid Waste MRF<br>- AdaptiveARC System<br>- Motors/Pumps, Refractor Layer, Torches | General Inflation | 5, 10, 15 |
| Energy<br>- Diesel<br>- Propane | Diesel Price Escalation | 1 through 20 |
| Water for Gasification System | Water Price Escalation | 1 through 20 |
| Minor Maintenance and Consumables for Gasification<br>- Minor Part Replacements<br>- Oil and grease<br>- Sodium hydroxide, lime, bio-filters | General Inflation | 1 through 20 |
| Wages<br>- Solid Waste MRF<br>- AdaptiveARC System | General Inflation | 1 through 20 |
| Diversion and Landfill Transport Costs<br>- Arcata – green waste<br>- Ukiah – food waste<br>- Willits – recycling<br>- Landfill – inerts | Diesel Price Escalation | 1 through 20 |
| Tipping Fees<br>- Ukiah – food waste<br>- Landfill – inerts | Fixed rate | 1 through 20 |
| Anaerobic Digestion<br>- Food waste | General Inflation | 1 through 20 |
| **Revenues Sources** | | |
| Bulk Recycling Revenue | General Inflation | 1 through 20 |
| Mixed Recycling Revenue | Fixed rate | 1 through 20 |
| Ash Sales | General Inflation | 1 through 20 |
| Electrical Sales<br>- Retail to HWMA<br>- To grid | Electricity Price Escalation | 1 through 20 |
| HWMA MSW Tipping Fee | General Inflation | 1 through 20 |