

## Integrated Waste to Energy and Liquid Fuel Plants: Key to Sustainable Solid Waste Management

Bary Wilson, Ph.D.  
Barry Liss, Ph.D., P.E  
Brandon Wilson, Ph.D., P.E

February 2020

EnviroPower Renewable, Inc.

7301A Palmetto Parkway Rd.  
Suite 206B Boca Raton, FL 33433

## Table of Contents

Executive Summary.....	3
Introduction .....	4
Background .....	4
Plastics.....	5
Plastics Recycling.....	6
Diesel Fuels .....	6
Premium Diesel .....	7
Biodiesel and Renewable Diesel .....	8
Polymer Structures and Their Effects on Thermal Cracking Product Composition .....	9
Conversion of Plastics to Liquid Fuel by Pyrolysis.....	13
Hydrothermal Conversion of Plastics to Fuel.....	14
Automated mechanical sorting of plastic types for optimal product fuel.....	15
Thermal Conversion of Combustible Solid Waste to Generate Power .....	15
Gasification .....	16
Liquid Fuels from Pyrolysis of Automotive Tires.....	19
Integrated Waste to Energy and Liquid Fuel Plant .....	20
Environmental Advantages of an Integrated Approach .....	22
Gasification .....	22
Plastics to Liquid Fuel.....	23
Sustainability.....	23
Environmental Advantages of plastics to ultra-low sulfur diesel fuel .....	23
Life Cycle Assessment of Greenhous Gas Emission Equivalentents.....	24
Life Cycle Assessment of Plastics to Liquid Fuel Conversion Processes.....	25
Economic and Commercial Advantages of an Integrated Approach .....	25
Summary .....	26
References .....	28

# Integrated Waste to Energy and Liquid Fuel Plants: Key to Sustainable Solid Waste Management

## Executive Summary

Collapse of the combustible recyclables market caused by the withdrawal of China has necessitated substantial changes in the ways in which municipal solid waste (MSW), including construction and demolition waste, is managed. An interim solution in many jurisdictions has been to place formerly recycled combustible materials into landfills. This approach is unsustainable and leads to acute waste management problems as landfill airspace dwindles. At the same time, a combination of tightening air emission standards, increasing acceptance of recycling, and aging plants, has led to the abandonment of waste incineration in many parts of the US. Shut down of waste to energy incinerators has served to exacerbate the problems with management of MSW.

Air fed gasification is a versatile and environmentally responsible thermal treatment technology for the conversion of combustible MSW to energy. In gasifiers, waste is heated in an oxygen starved atmosphere to produce a hydrogen-rich fuel gas that can be cleanly combusted to raise steam for turbine generators. When biomass (contemporary or cellulosic carbon) waste is used as the only fuel for the gasifiers, the electrical energy generated is considered renewable.

Plastics and synthetic fiber components of solid waste are produced from fossil hydrocarbon sources including coal, petroleum or natural gas and are not considered renewable fuels for thermal waste to energy. However, most plastics can be thermally treated to produce high quality liquid hydrocarbon fuels at yields that make the process economically attractive. The calorific value of biomass fuel is roughly 13 MJ/kg, while calorific values of plastics range up to 42 MJ/kg, making the latter more valuable per ton as motor fuel than as fuel for making electricity.

This paper describes an integrated solid waste management system in which biomass and fossil carbon-based components are sorted from incoming solid waste. Biomass components are gasified to produce clean renewable electrical energy. Plastic components are hydrothermally processed in a separate plant to produce diesel fuel oil as well as a metallurgical coke. Separate processing of the contemporary and fossil carbon components of solid waste in this manner is environmentally cleaner and economically more attractive than incineration of unsorted bulk waste to make electricity.

Depending on prevailing market prices for tipping fees, electrical power, and liquid hydrocarbon fuels, a facility that treats biomass carbon and fossil carbon wastes separately, as described here, can achieve rates of return that are more than twice those of conventional waste to energy plants, even when such plants operate on biomass to generate renewable energy.

## Introduction

Sustainable management of municipal solid waste (MSW) is of growing concern as the international market for formerly marketable recyclable waste materials such as plastics, cardboard and paper collapses<sup>[1,2]</sup>. With the effective withdrawal of China as the leading global customer for combustible recyclable materials, the already severe shortage of landfill airspace is now of central concern in many jurisdictions. This problem is exacerbated by the decommissioning of conventional waste incinerators, the unwillingness in many populated areas to permit new landfills, and the increasing volume of combustible materials, especially plastics, entering the waste streams. With few exceptions, governmental responses to the issue of improperly managed solid waste range from little or no meaningful action to an outright prohibition on new landfills, resulting in substantial increases in gate fees at existing waste disposal facilities.

There is widespread recognition that biomass components of MSW <sup>[3]</sup> can be beneficially used as renewable fuels for power generation, and that most fossil carbon derived waste in the form of plastics can be chemically recycled for re-use as fossil fuels at economically viable yields<sup>[4,5,6]</sup>. Nonetheless, in many jurisdictions the response has been to export waste or return to incineration of minimally sorted waste, or to mass burn of as-delivered waste.

This paper describes an integrated thermal conversion process that is applicable to dry sorted combustible solid waste comprised mainly of biomass and plastics, such as would meet the EU specification for solid recovered fuel (SRF), or to source separated plastics waste.

Process components include a waste reception and sorting facility where the incoming SRF is separated into plastics, cellulosic materials, metals and inerts. After separation, cellulosic carbon solid waste is gasified to generate renewable electrical energy. Mixed plastics (fossil carbon components) are thermally cracked in a catalytic pyrolysis plant to produce a mid-distillate hydrocarbon fuel. Existing technologies that enable the construction and operation of such a facility are discussed, as are the many environmental and economic advantages.

## Background

Combustible municipal solid waste (MSW) components can be classified according to the provenance of the carbon they contain. Biomass, comprised of cellulosic or contemporary carbon, including wood, cardboard, paper, natural fiber textiles, green waste, and agricultural waste, is considered as a renewable fuel. Combustion of wastes derived from coal, natural gas, or petroleum add new fossil carbon to the atmosphere when burned and are therefore not considered a renewable fuel. During the waste sorting process, non-combustible components

such as metals and so called “inerts” (glass, masonry, ceramics concrete, etc.) are removed from the combustible materials before they are recycled or used for fuel.

Fossil carbon waste includes plastics (synthetic polymers) that are ubiquitous as packaging, toys, plumbing and other construction materials, automotive parts, and a variety of single use and long-term use consumer goods. Motor vehicle tires are manufactured using synthetic polymers such as polybutadiene, as well as natural latex rubber. The use of carbon black and sulfur in the manufacture of tires requires that they be thermally converted to fuel in processes that are more complex than those used for most consumer plastics.

## Plastics

Plastics are polymers generally made from petroleum or natural gas and comprised of repeating, chemically bonded units called monomers. Monomers in plastics include organic compounds such as ethylene, propylene, butadiene, styrene, phenol, and vinyl chloride. In production the monomers are reacted to form polymer chains. These polymers can be produced by condensation reactions, wherein two molecules chemically bond, usually with the loss of water or an alcohol, or by addition reactions. Polymer chains are said to be crosslinked when monomers of one chain bond with those in another chain. Crosslinking can alter physical properties of the polymer such as pliability, tensile strength, or resistance to chemical attack. For purposes of recycling, it is convenient to differentiate between polymers classified as thermoplastics as compared to thermoset plastics.

Thermoplastic resins do not crosslink during curing. The curing process is thus completely reversible as no chemical bonding between polymer chains takes place. Thermoplastics soften when heated and become more fluid as additional heat is applied. When heated to sufficient temperatures thermoplastics, such as polyethylene terephthalate (PET), polypropylene (PP) or polystyrene (PS) will reach their glass transition temperature (100 °C for PS), at which these plastics melt, allowing them to be formed into pellets for reuse.

Thermoset plastic resins, such as polyurethane, polybutadiene, and melamine, once formed and cooled, cannot simply be re-melted. While a thermoplastic monomer has only two reactive ends for linear chain growth, thermoset monomers must have three or more reactive ends, allowing its molecular chains to crosslink in three dimensions during the curing process by forming irreversible chemical bonds. The cross-linking process eliminates the risk of the product re-melting when heat is applied, making thermosets ideal for high-heat applications such as electronics and appliances. Polybutadiene (**Figure 5**) is an example of a crosslinked polymer thermoplastic used as a synthetic rubber in the manufacture of tires.

## Plastics Recycling

Preferred methods for recycling plastics depend on their chemical structure<sup>[6]</sup>. For purposes of recycling by pyrolysis or hydrothermal conversion<sup>[7]</sup> to form liquid fuels, it is convenient to differentiate among polymers that are linear or crosslinked, as well as those comprised of saturated linear hydrocarbon chains (HDPE, LDPE and PP), and those that are unsaturated or include aromatic rings (PET, PS), or heteroatoms (PVC) in their structure. **Table 1** below lists the most frequently encountered waste plastics by RIC number.

Table 1. RIC numbers for common plastics encountered in MSW streams

RIC #	Name	Main Use
1	Polyethylene terephthalate (PET)	Soft drink & water bottles,
2	High Density Polyethylene (HDPE)	Water pipes, milk bottles, buckets
3	Polyvinyl Chloride (PVC)	Plumbing, cable insulation, records
4	Low Density Polyethylene (LDPE)	Squeeze bottles, cling films, lids
5	Polypropylene (PP)	Kitchenware, disposable cups,
6	Polystyrene (PS)	Egg cartons, packing peanuts, disposable cutlery
7	Other (Polycarbonate, ABS, etc.)	PC: lenses, compact discs / ABS: Plumbing /

## Diesel Fuels

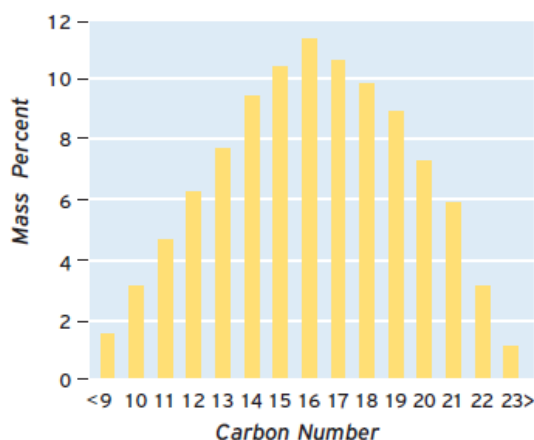
As described in more detail below, petroleum diesel fuel is a complex mixture of saturated, partially unsaturated and aromatic hydrocarbon compounds with carbon numbers in the range from about C9 to C22, including mostly paraffins, naphthenes, olefins and aromatics<sup>[8]</sup>. Each of these compound classes has different chemical and physical properties, and their different proportions are what makes one diesel fuel different from another. For compounds in the same class, boiling point increases with carbon number.

For compounds of the same carbon number, the order of increasing boiling point by class is generally as follows: paraffin, naphthene, and aromatic. As a compound class, the proportion of aromatics in diesel fuels should not exceed 35% by volume because aromatics tend reduce the energy content and cetane rating of the fuel. Motor diesel fuel distillate has a middle boiling point of approximately 500 °F. According to API and ASTM specifications, diesel fuel must have a minimum flash point of 100 °F an API gravity that falls in the 34 to 40 range.

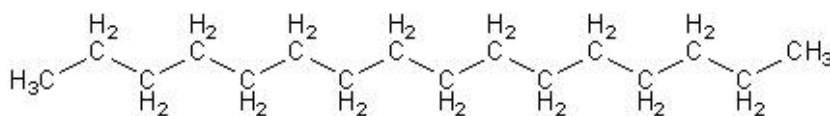
It must be 90% recovered at a distillation temperature of 540 °F for No.1 diesel, and between 550 °F and 640 °F for No. 2 diesel. Diesel fuel oil is designed for use in compression ignition engines. Unlike lighter distillate gasoline fuels with a midrange carbon number of C8 used in spark ignition reciprocating engines, diesel engine fuel is formulated to ignite from the heat of

compression at ratios between about 18:1 and 23:1. Lower compression ratios, down to 16:1, have been used to reduce NO<sub>x</sub> emissions.

**Figure 1** shows the components of diesel fuel as a function of carbon number. Gasoline blends are given an octane rating as a measure of performance (mainly ignition stability) against pure octane (C<sub>8</sub> H<sub>18</sub>). Diesel fuel quality is measured against hexadecane or cetane, the hydrocarbon shown below in **Figure 2**. The cetane molecule (C<sub>16</sub> H<sub>34</sub>), is a saturated (paraffinic) straight chain hydrocarbon. The term saturated, when referring to hydrocarbons, means that there are no carbon-carbon double bonds in the structure, and hence there are as many hydrogen atoms along the chain as chemically possible.



**Figure 1.** General composition of diesel fuels in terms of mass percent as a function of carbon number <sup>[8]</sup>



**Figure 2.** Chemical structure of cetane, a primary constituent of diesel fuel

Cetane numbers relate to the fuel ignition time delay in compression ignition engines. Diesel fuel in the US must have a cetane number of at least 40. The shorter the ignition delay time, more complete is the combustion of the fuel in the combustion chamber, and the better the engine performs. Diesel fuel formulators use a "calculated" method to determine cetane numbers. Two standards for determining calculate cetane rating are ASTM 4737 and ASTM D976. These two tests use fuel specific gravity and boiling points to derive a calculated cetane ratings. The cetane numbers for a variety of diesel fuels are shown in **Table 2**.

**Table 2.** Cetane numbers (#) for various diesel fuels <sup>[7]</sup>

Diesel Fuel	#
Regular Diesel	48
Premium Diesel	55
Biodiesel (B100)	55
Biodiesel Blend (B20)	50
Synthetic Diesel	55

### Premium Diesel

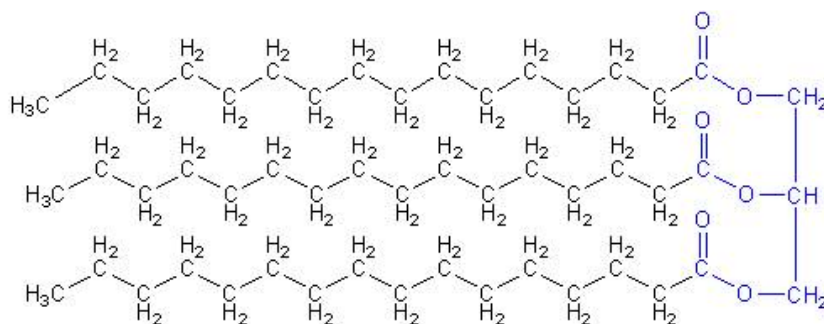
Specifications have been developed by the National Conference of Weight and Measures (NCWM) for a Premium Diesel. This specification ensures that properties such as cetane number, low-temperature operability, stability, lubricity, detergency, and heating value



are within tightly controlled limits<sup>[8]</sup>. Premium diesel fuels demand a higher price in the market, due to their consistent and near optimal performance as a compression ignition engine fuel.

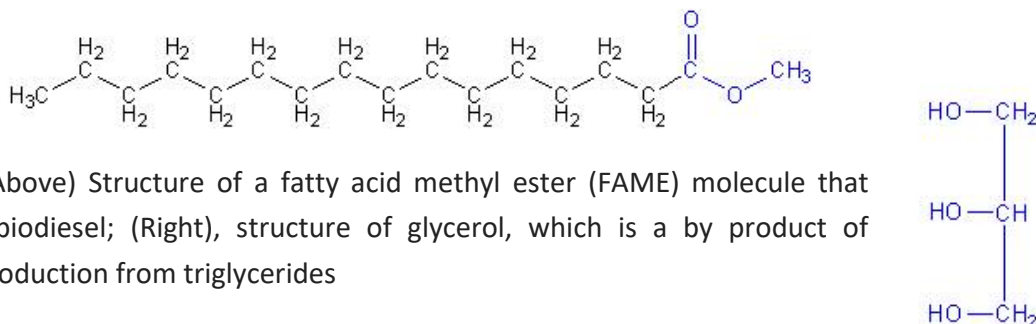
### Biodiesel and Renewable Diesel

Biodiesel is made by chemical modification of vegetable oils or animal fats. The starting material is normally a triglyceride with the general chemical structure shown in **Figure 3**. A typical biodiesel hydrocarbon is shown in **Figure 4**. This example is a C16 alkane backbone that terminates in an ester group or moiety (COOCH<sub>3</sub>) in a reaction as described below.<sup>[9]</sup>



**Figure 3.** general structure of a vegetable oil or animal fat triglyceride

To obtain the fatty acid methyl esters molecules that comprise biodiesel (**Figure 4**), the triglycerides are reacted with methanol in the presence of a base. This process yields individual fatty acids, some of which may have carbon=carbon double bonds along their hydrocarbon chain, as well as glycerol. Depending on the source, triglycerides can contain a variety of fatty acids.



**Figure 4.** (Above) Structure of a fatty acid methyl ester (FAME) molecule that comprises biodiesel; (Right), structure of glycerol, which is a by product of biodiesel production from triglycerides

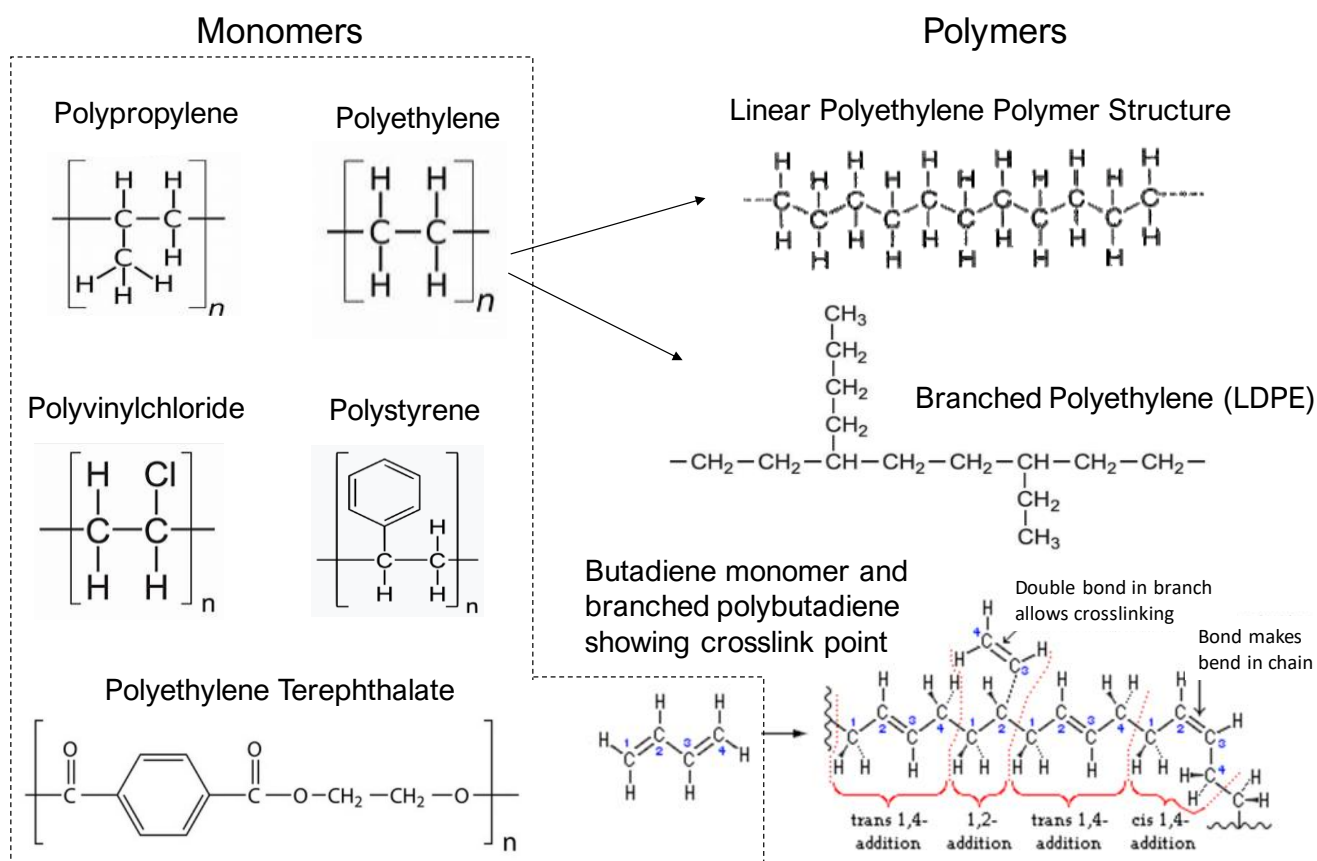
Biodiesel contains essentially no sulfur or aromatics and generally creates lower emissions of particulates and carbon monoxide than conventional petroleum diesel. The calorific value of biodiesel is slightly lower than that of conventional diesel. Although biodiesel has good lubricity properties, it also has a relatively high pour point, which could limit its use in cold weather. Because of the oxygen atoms in the ester group, biodiesel is also more susceptible to oxidative degradation than petroleum diesel, so biodiesel fuels degrade more rapidly than conventional diesel fuel. This property may also lead to increased biological growth during storage. The general recommendation of diesel engine manufacturers is that biodiesel be blended



to a maximum proportion of 5% (B05) with petroleum diesel for motor fuel use. Hydrogenation of biodiesel essentially eliminates the oxygen, resulting in a higher quality, cleaner burning, paraffinic fuel designated as **Renewable Diesel**.

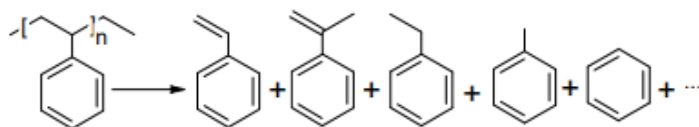
## Polymer Structures and Their Effects on Thermal Cracking Product Composition

Chemical structures for several common monomers, and examples of linear and branched polymer chains to form polyethylene and polybutadiene, are shown below in **Figure 5**.



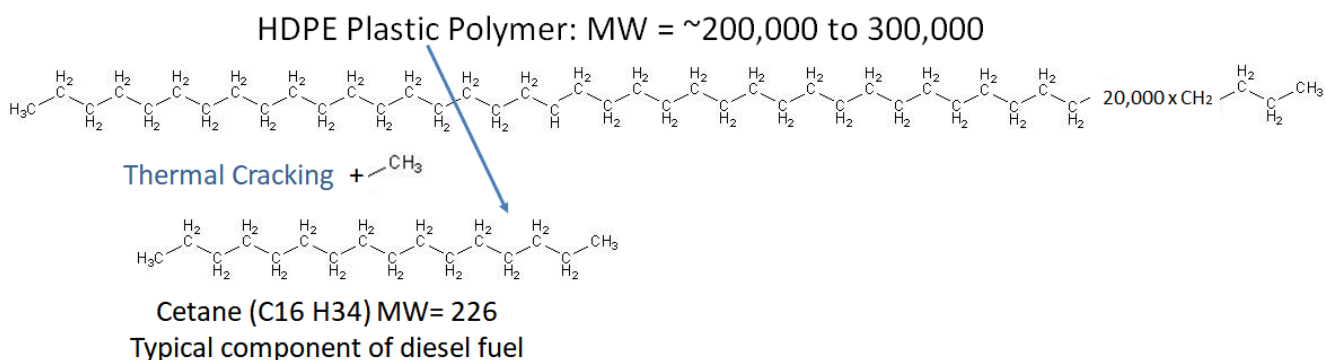
**Figure 5.** (Left) Chemical structures of common monomers used to make common plastics (Right) examples of linear(HDPE) and branched (LDPE) polymers of polyethylene (PE) and the more complex structure of polybutadiene with the addition reactions and a crosslink branch point indicated

The nature of the liquids obtained from plastics depends on the design of the pyrolysis system, any catalysts used, and the mixture of plastics used as feedstocks. Thermal decomposition products of some thermoplastic polymers, such as polystyrene (PS), are comprised largely of alkylated styrenes, as shown in **Figure 6**. Straight or branched chain thermoplastics plastics yield mostly paraffins, naphthenes and olephins.



**Figure 6.** Chemical structure of aromatic products from the catalytic pyrolysis of polystyrene

HDPE, LDPE and polypropylene (PP) materials yield basically hydrocarbon chains of varying length, both saturated and unsaturated, which result from scission along the non-crosslinked polymeric chain (**Figure 7**). Liquid yields from non-catalytic pyrolysis of HDPE has been reported as high as 70%.



**Figure 7.** Cracking of straight chain polyethylene molecule to obtain cetane

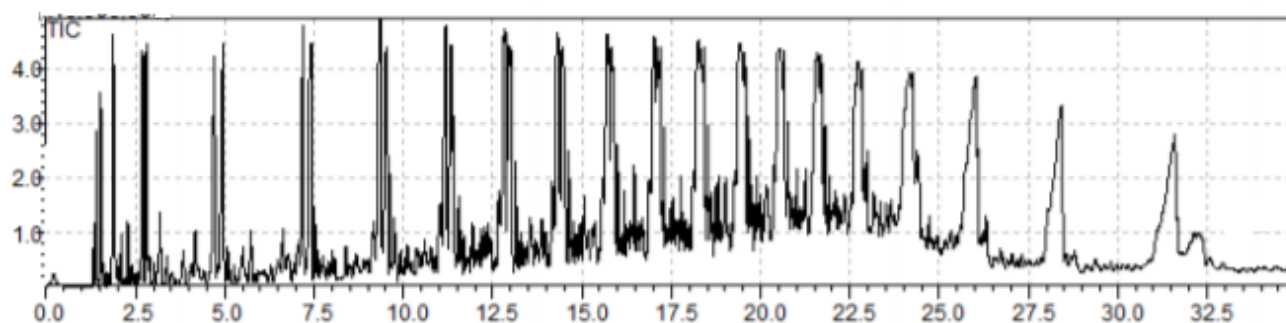
Most plastic polymers thermally decompose to smaller, stable molecules that were not constituents of the original polymers. For example, without the use of catalysts, polymers such as polyethylene thermally decompose to a series of mainly alkanes and alkenes (paraffins, naphthenes and olefins). The gas chromatogram of the pyrolysis products from waste PE on the following page (**Figure 8**) shows a series of mainly alkanes and alkene eluting in groups according to carbon number. Hexane (C<sub>6</sub>) components were detected starting at 1.9 minutes, octene (C<sub>8</sub>) eluded at 4.75 minutes, normal undecane (C<sub>11</sub> H<sub>24</sub>) was detected at 9.55 minutes and the last peak that could be identified by GCMS, heneicosane (C<sub>21</sub> H<sub>44</sub>) eluded at 28.3 minutes.

The gas chromatogram in **Figure 8** shows the presence of alkanes and alkenes from approximately C<sub>5</sub> through C<sub>21</sub>. Higher molecular weight compounds were likely in the product mix but did not elute over the time and temperature range of the analysis. Fractional distillation of the material that was eluded from the gas chromatograph could be adjusted to yield a gasoline cut, a JP-8 cut, and a diesel fuel cut. Pyrolysis of mixed plastics (catalytic or non-catalytic) do not yield such well-defined products.

It should be noted that the gas phase hydrocarbons (especially methane, ethane, propane and butane) formed during thermal cracking of the polymers carry off a disproportionate amount of hydrogen relative to their carbon content. Compounds eluting in the gas chromatogram <sup>[6]</sup> in

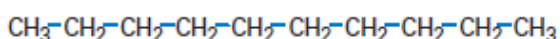
**Figure 8** are mainly straight chain or branched paraffins, naphthenes and olefins with typical structures shown below in **Figure 9**.

The five and six member rings in the naphthenes are saturated. Saturated straight chain hydrocarbons are also designated as alkanes. Those with C=C double bonds are alkenes. The classes of compounds shown below are the main constituents of petroleum derived diesel fuels.



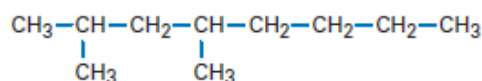
**Figure 8.** Gas chromatogram of pyrolysis products high density polyethylene [6]

#### n-Paraffin



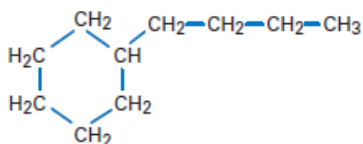
*n-Decane*  $\text{C}_{10}\text{H}_{22}$

#### Isoparaffin



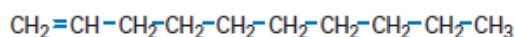
*2,4-Dimethyloctane*  $\text{C}_{10}\text{H}_{22}$

#### Naphthenes



*Butylcyclohexane*  $\text{C}_{10}\text{H}_{20}$

#### Olefin



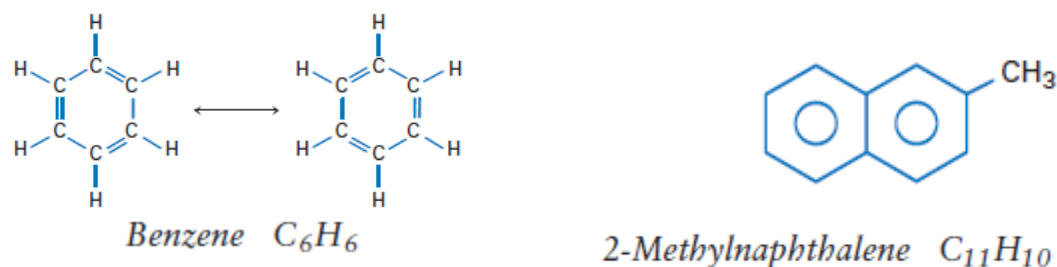
*1-Decene*  $\text{C}_{10}\text{H}_{20}$

**Figure 9.** Chemical structures of typical n-paraffins (straight chain saturated hydrocarbons), isoparaffins (branched chain saturated hydrocarbons) naphthenes (saturated cyclic hydrocarbons) and olefins (unsaturated hydrocarbons with one or more double bonds) [8]

Compounds with benzene rings in the structure are designated as aromatic. Compounds with multiple fused benzene rings are designated as polycyclic aromatic. **Figure 10** below shows the structure of a single benzene ring as well as a substituted polycyclic aromatic.

Again, as shown in **Table 3** below, calorific values tend to increase with increasing H/C ratios. This, and the greater chemical stability of aromatic compounds, which delays their ignition

relative to alkanes under heat and pressure, are reasons for their lower cetane rating. The proportion of aromatic compounds in diesel fuel is limited to 35% by volume because of this lower cetane rating.



**Figure 10.** (Left) Benzene ring structure showing the two possible configurations of the double bonds in the ring, (Right) fused benzene rings comprising a polycyclic aromatic compound with a methyl substitution<sup>[8]</sup>

As shown in **Table 3**, calorific value in hydrocarbon fuels tends to be a function of the hydrogen to carbon (H/C) ratio <sup>[10]</sup>.

**Table 4** below shows the carbon number and distillation temperature ranges for the main petroleum derived fuels. The H/C ratio is an important factor in preparation and blending of hydrocarbon fuels, including the pyrolysis oils derived from plastics.

**Table 3.** Hydrogen to carbon ratios and calorific value of four hydrocarbon fuels.

Fuel	H/C Ratio	CV (MJ/kg)
Hydrogen	N/A	142
Natural Gas	4.0	54
Gasoline	1.85	45-47
Diesel Fuel	1.89	46

**Table 4.** Carbon number and distillation temperature ranges for the petroleum derived fuels

Hydrocarbon Product	Typical Carbon Range	Boiling Point Range (°C)
Gas Phase Hydrocarbons	C1 – C5	< - 12
Liquid Fuel Scan	C6 – C50	N/A
Gasoline	C6 – C12	100 - 150
JP-8 (Jet A)	C8 – C18	200 - 300
Diesel Range	C8 – C24	200 - 300
Heating Oil	C9 – C24	200 - 300
Bunker C	C10 - C26	350 - 450
Heavy Fuel Oils	C9 - C50	350 - 450

- Carbon range for gasoline, diesel and heating oil may differ from state to state.
- These ranges are the most common.

## Conversion of Plastics to Liquid Fuel by Pyrolysis

Pyrolysis is a process by which synthetic polymers derived from petroleum-based chemicals can be thermally cracked to form a mixture of gas and liquid phase hydrocarbons and a residual carbon-rich char or coke. In pyrolysis, the plastics is heated indirectly in a reactor, such as the one shown in **Figure 11**, from which oxygen has been purged with an inert gas such as nitrogen to prevent combustion of the hydrocarbon products. Gas to liquid product ratios for catalytic and non-catalytic thermal cracking of plastic polymers tend to increase with increasing temperature, as does the amount of char.



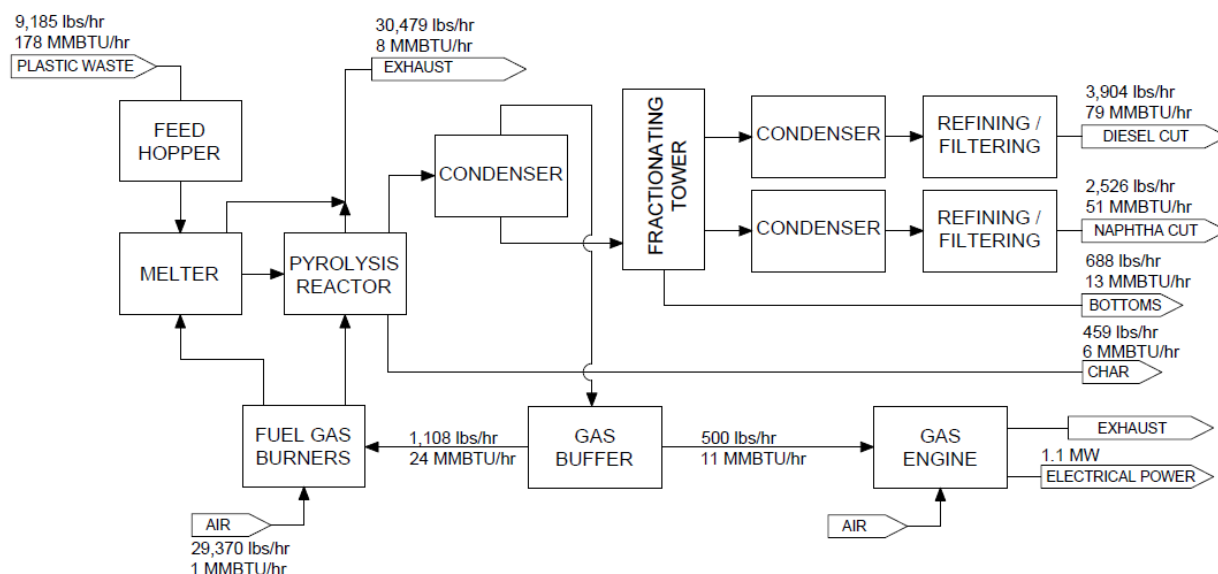
**Figure 11.** Commercial thermocatalytic cracking plant operating on sludge [12]

Not only are liquid yields higher at lower pyrolysis temperatures when catalysts are used, the liquids themselves tend to have higher calorific value and are of generally better performance as fuels [11]. Thus, the use of catalysts in the pyrolysis of plastics helps to reduce the thermal energy required for conversion and tends to yield greater yields of useful products at lower temperatures. Zeolite catalysts are the most commonly used in thermal conversion of plastics to liquid fuels. However, other catalytic systems can allow more product selectivity with higher yields, especially when converting tires (mainly polybutadiene) to liquid fuels.

As described above, plastics are comprised of synthetic polymers manufactures from petroleum, natural gas, or coal product raw materials. These polymers can be thermally cracked into smaller stable, gas or liquid phase hydrocarbon molecules that can be used as fuel. A solid phase (mainly carbon) char is also produced during a thermocatalytic process. (This process can also be used with tires, oil sludge, or tar sands as a feedstock). Of primary interest here is the conversion of plastics into mid-range distillate hydrocarbons using thermocatalytic cracking [4,5,6,7]. Pyrolysis is commonly used as the initial step for converting plastic polymers to gas phase and liquid phase fuels. When carried out in an inert gas atmosphere, there is no oxidation of the hydrocarbon products allowing for the best possible recovery of hydrocarbon fuels after catalytic cracking.

**Figure 12** below is a block diagram showing the main functional components of a simple thermocatalytic plastics conversion plant. The thermal reactor used for pyrolysis is indirectly heated and is purged with an inert gas such as nitrogen. The gas phase pyrolysis products are passed through a catalyst bed that promotes the further decomposition into eventual liquid and gas phase hydrocarbons. These are then separated by fractional distillation. The residual char is

removed from the pyrolysis chamber and used as carbon black. Gas phase hydrocarbons that do not condense out are used as fuel for the reactor and melter burners.



**Figure 12.** Block diagram of a basic plastics to liquid plant

## Hydrothermal Conversion of Plastics to Fuel

In hydrothermal liquefaction (HTL), superheated water at high pressures is used in a simple, well controlled system to convert carbonaceous waste to liquid fuel.<sup>[12,13]</sup> At temperatures well above the standard boiling point of water, and pressures above a few hundred psi, the properties of water change, making it a good solvent for most plastics as well as biomass organic materials. This superheated water conversion requires substantially less thermal energy than steam extraction because the water is held in the liquid phase by the high pressure, thus avoiding the need for the additional energy required to evaporate the water. **Figure 13** shows a commercial HTL plant that converted turkey offal to fuel.



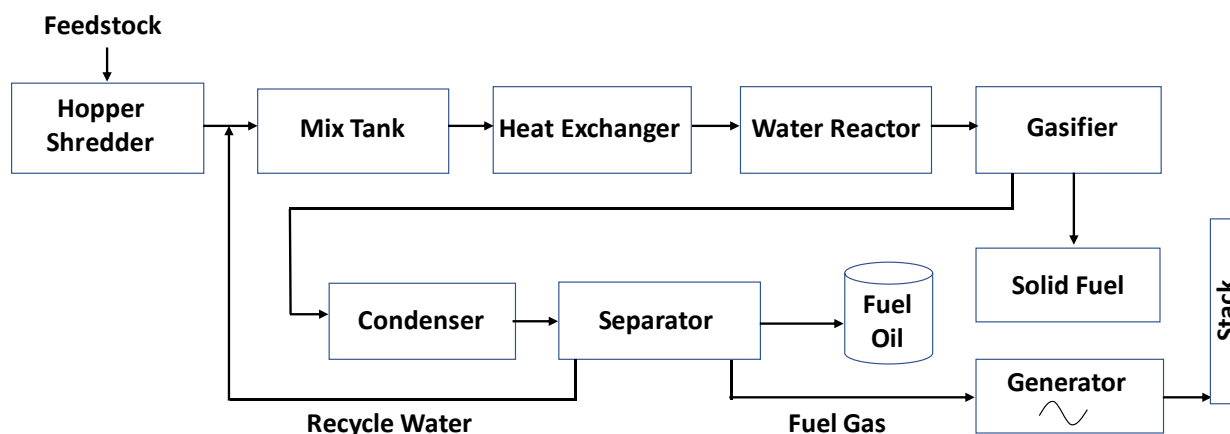
**Figure 13.** Commercial HTL plant operating turkey offal

HTL conversion of mixed plastics (fossil carbon) to fuel oil has been demonstrated in the scientific literature <sup>[12]</sup>, as has hydrothermal conversion of biomass (cellulosic carbon),<sup>[14]</sup> as well as unseparated municipal solid in general waste (plastic plus biomass).<sup>[15]</sup> HTL fuel oil yields depend on the feedstock. A metric ton of mixed plastic yields up to 700 L of a #2 fuel oil.



Dry biomass yields about 160 L, while ton of food waste (mostly water) yields about 40L. Addition of a catalyst can increase conversion and alter the gas phase to liquid phase product ratio. Production of methane gas, used as fuel within the plant, also varies according to feedstock in proportion to the liquid fuel yield. Coke solid fuel yield is inversely proportional to the amount of available hydrogen in the feedstock or reactor environment.

**Figure 14** below shows a block diagram of the process flow for an HTL system that produces diesel fuel, a methane gas used for process heating and to generate electrical power, and a coke solid fuel product.



**Figure 14.** Simplified process flow diagram of an HTL system or conversion of plastics to fuels

#### Automated mechanical sorting of plastic types for optimal product fuel

Product quality from a plastics to liquid fuels plant can be optimized by selecting the proper plastics as feedstock. Mechanical sorting systems that use optical sensors and air jet separators to sort plastics according to their composition are commercially available. Plastics separation systems can be custom made to handle a variety of incoming waste streams and to provide cleanly separated plastics by polymer. Their cost is often justified by increased liquid fuel quality.

### Thermal Conversion of Combustible Solid Waste to Generate Power

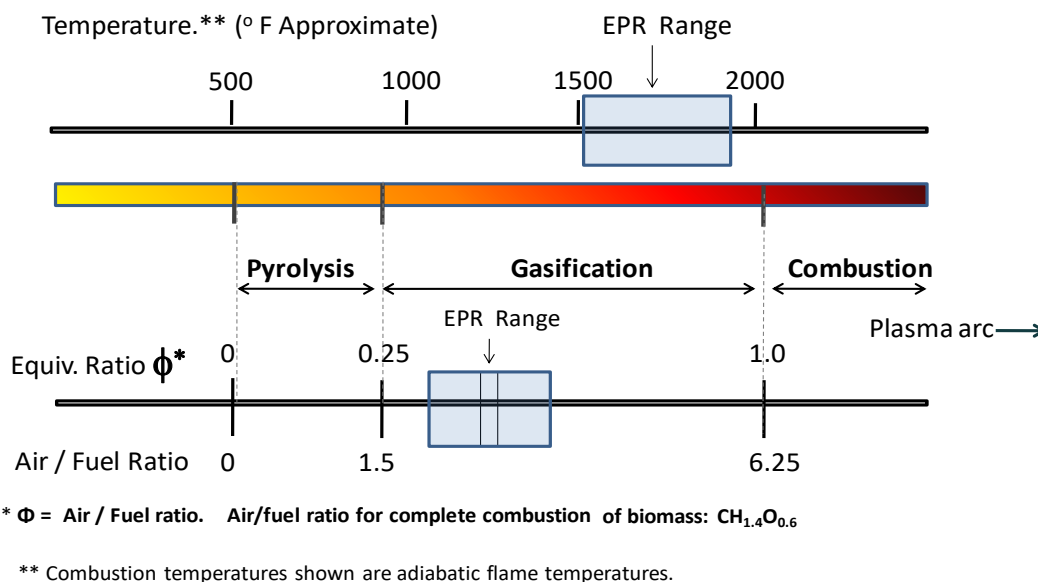
Combustible components of solid waste, whether from residential collection, construction and demolition debris, or industrial sources, is composed of biomass derived (cellulosic or contemporary carbon) and fossil derived carbon (from coal, petroleum or natural gas). Biomass derived materials including wood, cardboard, paper, natural textile fibers and leather are considered renewable because they come from plants or animals already in the carbon chain of the troposphere. Fossil carbon materials, including plastics, are not considered as renewable fuels



because their combustion adds carbon to the troposphere that has otherwise been sequestered underground as coal or petroleum liquids and gas for millions of years.

Thermal processing of combustible municipal and industrial solid waste has been practiced for centuries. This approach has progressed from open burning of materials in dumpsites to carefully controlled incineration to fire boilers in increasingly large and sophisticated steam power plants. For a review of thermal treatment practices for MSW, see Stantec. <sup>[16]</sup>

As shown in **Figure 15** below thermal treatment options for solid waste include pyrolysis and gasification along with incineration, or complete combustion in a controlled process. These three processes are distinguished mainly by the amount of oxygen available to support combustion, and the temperature range at which they operate. Pyrolysis processes can operate with no oxidant in direct contact with the material being treated. In this case, thermal breakdown occurs with little or no oxidation of the chemical products.



**Figure 15.** Temperature ranges and air / fuel ratios for pyrolysis, gasification and combustion

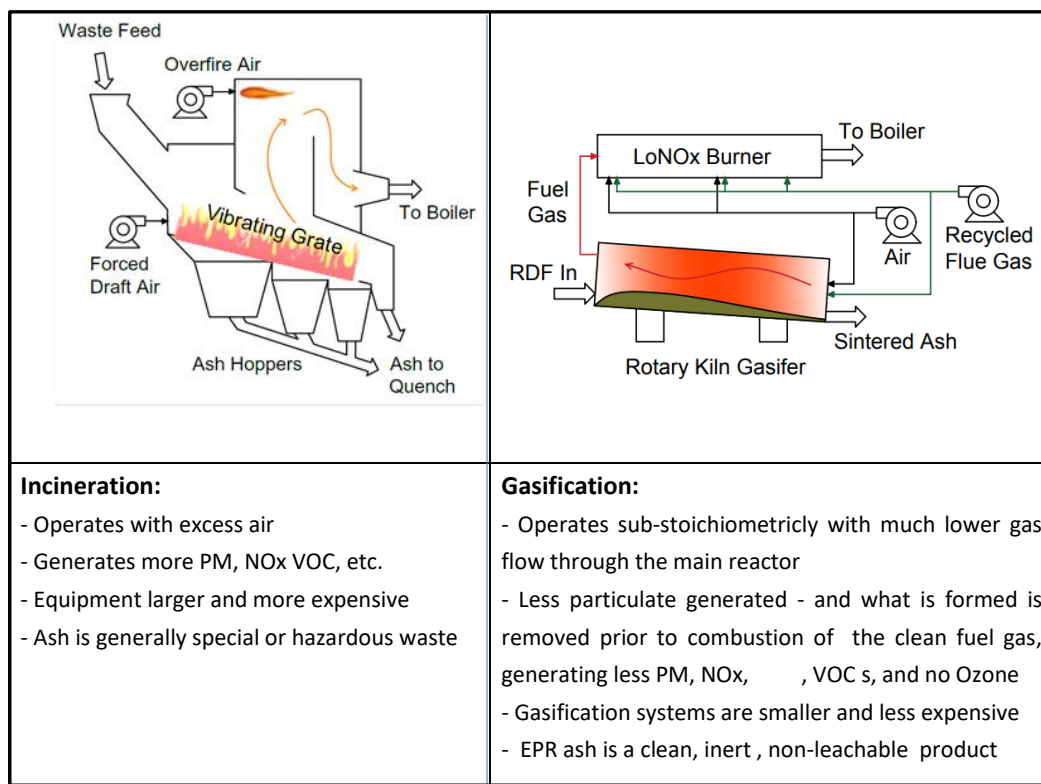
### Gasification

Gasification is a clean thermal treatment technology, ideal for smaller waste to energy plants producing from 10 to 50 MW. This technology is environmentally friendlier and less expensive than incineration and lends itself well to distributed generation electrical grid structures. Gasification is a process wherein carbonaceous materials are dissociated at high temperatures in an oxygen-starved thermal reactor to form a fuel gas comprised mainly carbon dioxide, carbon monoxide, hydrogen, methane, and water vapor. If the thermal reactor is air fed (as opposed to oxygen fed only), the fuel gas also contains nitrogen.

Incineration involves the complete combustion of the fuel, in this case solid waste, in a single reactor volume. Solid waste incinerators, mostly of moving grate design, are being shut down in many jurisdictions because of emissions and cost of operation. Where these older systems are being replaced with incinerators, they often operate in mass burn mode, mass, where there is little or no separation of the incoming waste. Hazardous wastes and inerts such as small appliances, are removed.

Metals, fossil carbon, biomass carbon, and non-combustible waste materials are dumped into a large concrete pit from which a grappling crane picks up material and deposits it into a moving grate. In some cases, recyclable metals are recovered from the incinerator ash.

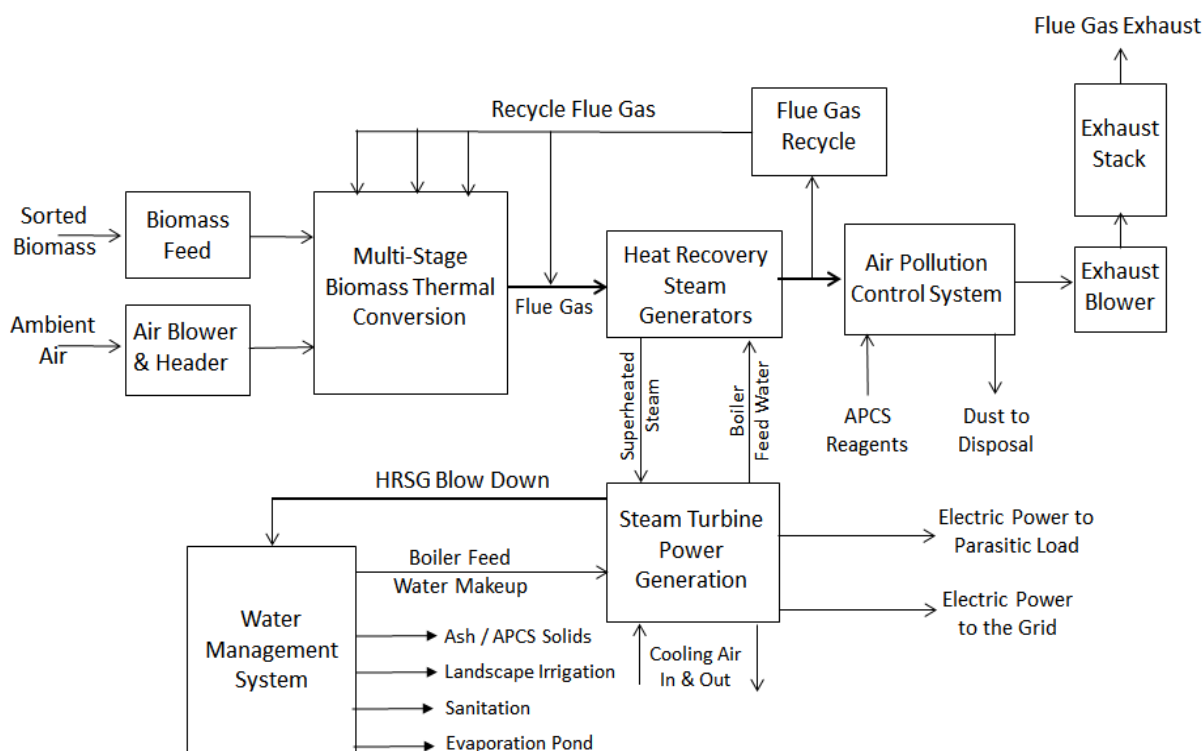
The significant differences between gasification and incineration are illustrated in **Figure 16** on the following page. Note that incinerators must be large enough to handle the mass flow of the combustion air plus the combusted fuel. It requires nominally six tons of air to completely oxidize one ton of carbonaceous fuel. In contrast, the gasification reactor requires approximately one third as much air to gasify a ton of fuel. The gasification reactor can therefore be smaller for a given amount of fuel and the mass flow through the reactor is substantially lower, as is particle entrainment.



**Figure 16.** Comparison of gasification and incineration for thermal conversion of biomass

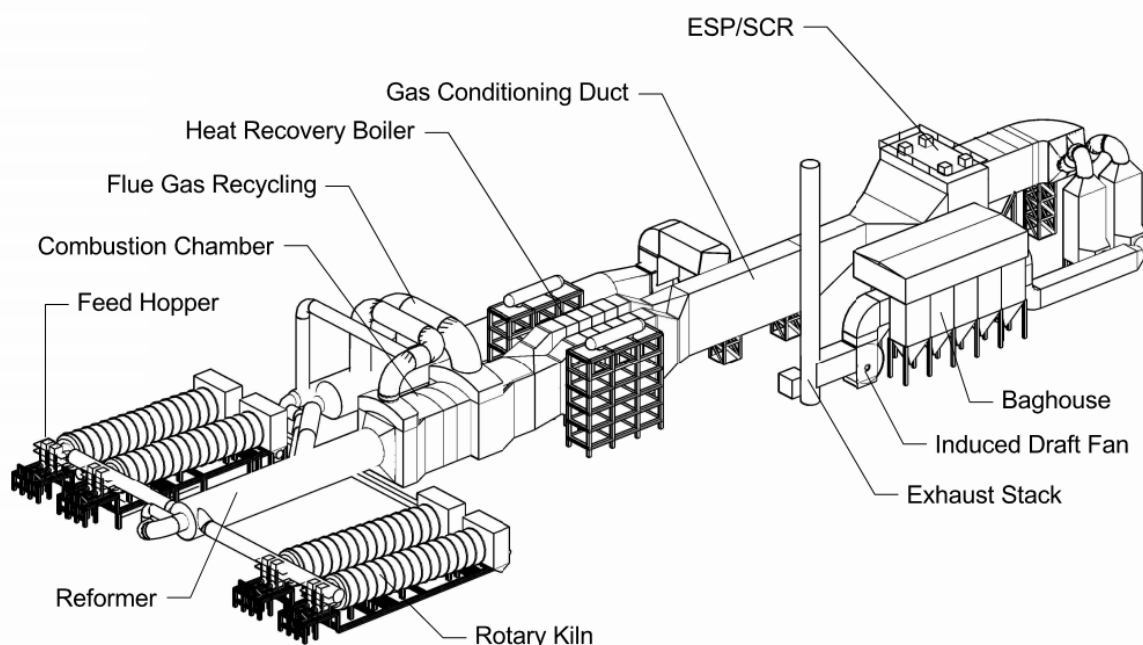
When using the steam Rankine cycle for generation of electricity, the hot fuel gas is combusted to generate steam in a heat recovery boiler. The steam is then used to drive a turbine generator. In smaller plants (ca. 10 MW or less) this low Btu fuel gas is sometimes cleaned and cooled and used to fire reciprocating engine gensets. However low Btu gas fired reciprocators are substantially less reliable than steam turbines. **Figure 17** is a block diagram of an EPR waste to energy gasification power plant. The EPR design uses rotary kilns as gasification reactors along with a patented flue gas recycle system to substantially reduce NO<sub>x</sub> emissions.

Since waste to energy plants are paid to take in fuel, thermodynamic efficiency need not be the top priority in plant design. In EPR plant designs the main emphasis is on reliability, safety, and lowest possible environmental impact. Air emissions from a 100 MW plant (comprised of two 50 MW units and processing some 3,000 tons per day) are low enough that it can be permitted as a minor source.



**Figure 17.** Block diagram of an EPR rotary kiln gasification power plant with flue gas recycle

**Figure 18** below is an oblique view drawing of the thermal island of an EPR gasification power plant. This low-profile design, with a horizontally oriented reformer and two low profile heat recovery steam generators, offers greatly reduced wind loading. This design can also be readily installed inside a building in areas where excessively cold or wet weather can interfere with proper operation or maintenance.



**Figure 18.** Oblique view of the thermal island of a gasification power plant showing the rotary kiln gasifiers, reformer, heat recovery boilers and flue gas clean-up system.

### Liquid Fuels from Pyrolysis of Automotive Tires

Automotive tires contain natural latex and synthetic polymers that can be thermally cracked to obtain a hydrocarbon liquid. Polybutadiene comes in several forms and is the primary synthetic rubber used in tire manufacture. Other polymers used in tire making include natural latex rubber, halobutyl rubber, as well as reinforcing fabrics including rayon (a purified cellulose polymer), polyester, Nylon and Kevlar, the latter two having nitrogen containing monomers.

Sulfur is used in the vulcanization process to crosslink the rubber monomers. Other materials used in the manufacture of tires include sulfur carbon black, silica, textile fabrics and steel wire in the belts for reinforcement, and steel cable in the bead. Tires are commonly de-beaded prior to being thermally processed. Catalytic and non-catalytic thermal decomposition of tires can be used to recover fuel gas, pyrolysis oil, carbon black and steel wire.

Temperatures used in the pyrolysis of tires commonly ranges from 450 °C to 600 °C. **Table 5** below shows typical proximate and elemental analyses of tires. The manufacturer selected by EPR builds thermocatalytic plants that operate on waste tires oil sludge tar sand and mixed plastics.

**Table 5.** Proximal and elemental analysis of tire shreds and the percentages of gas, oils and carbon black, and steel wire obtained from pyrolysis

Proximate Analysis		Elemental Analysis		Pyrolysis Product Yield	
	wt%		wt%		wt%
Moisture	0.82	Carbon (C)	80	Pyrolytic Gas	10%
Volatiles	61	Hydrogen (H)	7	Pyrolytic Oil	36% - 42%
Fixed Carbon	32	Nitrogen (N)	0.4	Carbon Black	30% - 35%
Ash	4.0	Oxygen (O)	7	Steel Wire	12% - 15%
HHV (MJ/kg)	36.5	Other (including Sulfur)	5.4		

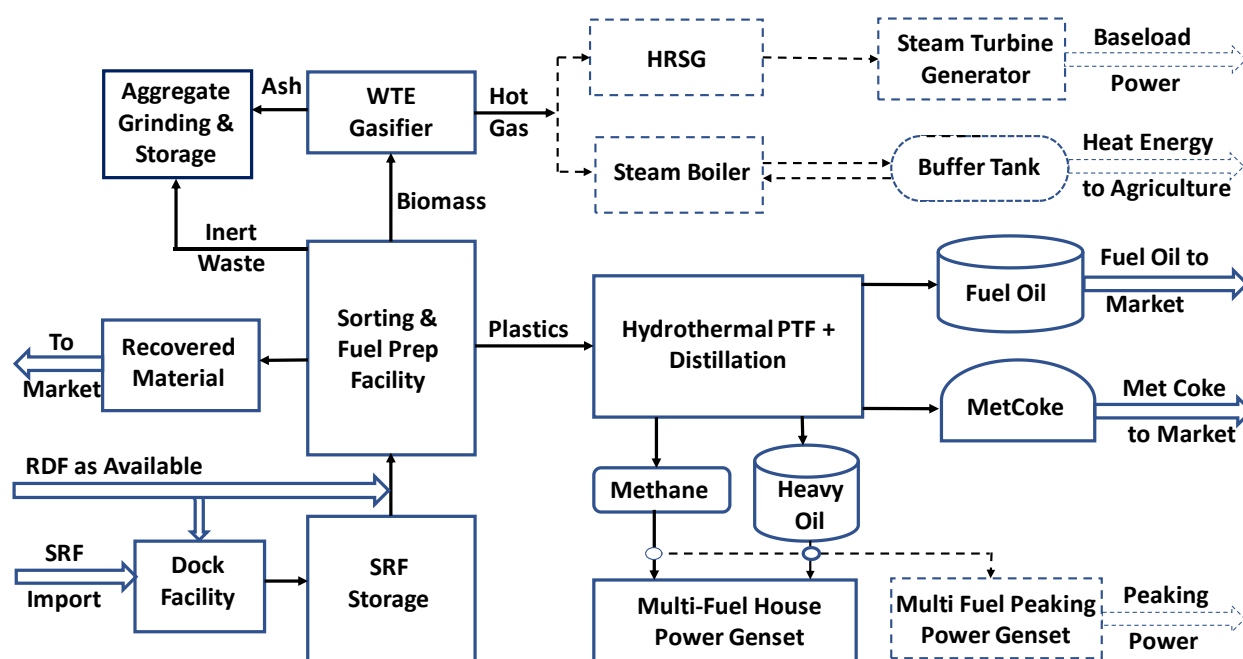
## Integrated Waste to Energy and Liquid Fuel Plant

Integration of biomass and plastics thermal conversion processes can provide operational, environmental and economic advantages. Generating electricity from biomass-only allows the power generated to be considered renewable. Likewise, producing liquid fuel from plastics that would otherwise be considered as solid waste and placed in landfill reduces the amount of new fossil carbon that must be extracted and refined to produce an equivalent amount of liquid fuel.

Additionally, the liquid fuel derived from plastics is ultra-low in sulfur and is therefore cleaner burning than most diesel fuels refined directly from crude oil. As described below, a study from Argonne National Laboratory found that diesel produced by thermal cracking of waste plastics requires up to 96% less energy to produce than fuel from crude oil. Finally, there are beneficial uses for the residual solid products from thermal conversion of biomass and plastics.

The carbon rich solid residue from hydrothermal liquefaction of plastics is better classified as a coke material. This can be refined to metallurgical grade (metcoke) used in steel production. Alternatively, it can be produced as a less valuable petroleum coke or metcoke and used as a solid fuel. Conventional pyrolysis produces a char solid residual material that is mainly carbon. If this material is of sufficient quality, it can be sold as carbon black. If no market can be found, the char can be used as a fuel in the gasification plant section of the integrated facility.

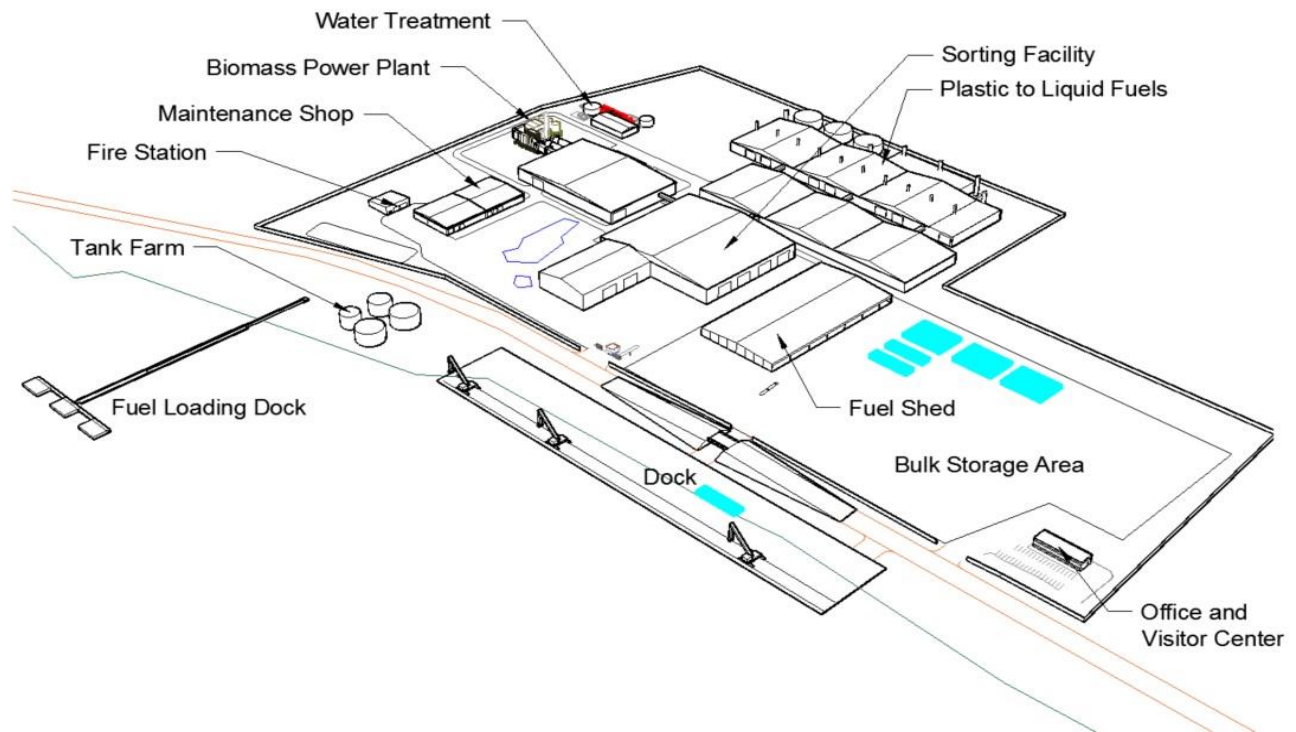
**Figure 19** below shows a block diagram of an integrated facility and the main raw material and product flows into, among, and out of the three main facility components. The sorting facility, plastics to liquid fuel pyrolysis plant and the biomass gasification plant are described in more detail below. Where markets exist, metals and some inerts can be bring in additional revenue.



**Figure 19.** Block diagram for an integrated waste to electric power and liquid fuels plant, operating on refuse derived fuel and from which there is no carbonaceous solid waste.

**Figure 20** shows the general layout of an integrated waste to energy - plastics to liquids plant. In this design, the incoming waste is unloaded onto the tipping floor where the biomass and fossil carbon components are separated. Plastics are further mechanically sorted into classes according to their compatibility with the pyrolysis system in use. In this case, pyrolysis is by a thermocatalytic system with mainly HDPE, LDPE and PP as feedstock. While some polystyrenes or PET materials may be added to the feed mix, no PVC is allowed.

The product liquid from the plant is intended to meet the main specifications for a No 2 diesel with an API gravity between less than 40, distillation temperature (90% volume recovered) between 540 °F and 640 °F, and an aromatic content or less than 35% by volume. This material is intended as a drop-in diesel blending material to be sold to bulk fuel suppliers in the local market. Alternatively, the full range distillate liquid materials from the plant can be sold to an oil refinery. This material would normally be added to the crude oil or elsewhere in the refining process with the various chemical components in the distillate emerging from the refining process in their respective carbon number, functional group and distillate ranges (see **Table 4**). Aliphatic linear and branched hydrocarbon polymers will be the primary feedstock for the HTL process used in the EPR Integrated facility described here. These constitute the cleanest and most readily converted among these feedstocks for which these plants are designed.



**Figure 20.** Oblique rendering of an integrated waste to energy and plastics to liquid fuels plant

## Environmental Advantages of an Integrated Approach

### Gasification

Air emissions from well designed and operated solid gasification plants fired with biomass sorted from construction and demolition debris and industrial waste are lower per kWh of energy produced than from any other combustion-based process. <sup>[17]</sup> Furthermore, gasification of a ton green waste biomass results in a much lower release of greenhouse gas equivalents (GHGe) to the environment than does placement of this same ton of biomass in a landfill, where most of it would eventually be anaerobically converted to CO<sub>2</sub> and methane (CH<sub>4</sub>).

This disparity holds even if the landfill is eventually equipped with a landfill gas recovery system. This is because methane is at least 25 times more effective as a GHG than CO<sub>2</sub>, and because much of the methane produced in a landfill is emitted through the working face before any kind of effective cover is in place or before landfill gas recovery systems are installed.

Rotary kiln gasification systems can be operated to produce an essentially carbon free inert inorganic sintered ash that is safe for use as a construction fill and need not be placed in a landfill. This inert sintered material should not be confused with the ash from MSW incinerators.



## Plastics to Liquid Fuel

The principle sources of air emissions from a plastics to liquid fuels plant comes from the operation of the gas burner used to heat the primary thermal (pyrolysis) reactor. These burners use the gas phase (non-condensable) hydrocarbon cut (nominally C<sub>1</sub>-C<sub>5</sub>) from the thermal depolymerization reactor as fuel. Concentrations of criteria pollutants in the exhaust gas from the burner are well below regulatory limits.

However, the primary environmental advantage of the PtL process is that it helps keep fugitive plastics out of the terrestrial and marine environments where they can pose a danger to wildlife and to humans. Plastics to fuels plants directly address the growing concern of fugitive plastics accumulation in the environment.

Solid residues from the plastics to liquid fuels are mainly a carbon-rich char that normally comprises some 10% of the mass of the plastic material fed to the system. In some markets this char material has a value as carbon black. If no market can be found for this material, it can be used as fuel for the gasifiers that operate at temperatures high enough to convert (“burn out”) the carbon portion of this material leaving a small amount of inorganic ash.

## Sustainability

Thermally treating solid waste is more environmentally responsible than placing it in a landfill or allowing it to move into the environment as fugitive trash. In the case of plastics, the extent to which these materials persist and pollutes the environment has long been recognized. It is estimated that some 12 million metric tons of plastic debris end up in the oceans of the world each year. This plastic slowly degrades over time from the action of UV and the mechanical effects of wind and salt water to form small particles designated as microplastics.

Microplastic particles have been detected in environments from depths of 30,000 feet in the ocean to an altitude of 5,000 feet in the Pyrenees mountain air some 60 miles from the nearest city, Toulouse. While the damage done to wildlife by plastics in the environment is widely known, the long-term health effects microplastics in the air and in drinking water have yet to be determined. Waste plastics are best converted to a hydrocarbon fuel, which fuel obviates the need to introduce an equivalent amount of newly pumped crude into the environment.

## Environmental Advantages of plastics to ultra-low sulfur diesel fuel

Argonne National Laboratory (ANL), part of the U.S. Department of Energy, has determined that using pyrolysis to convert non-recycled plastics into ultra-low-sulfur diesel (ULSD) fuel results in significant energy and environmental benefits. <sup>[5]</sup> These include: reductions

of up to 14 percent in greenhouse gas emissions, up to 58 percent in water consumption, and - up to 96 percent in traditional energy use when compared to ULSD from conventional crude oil.

### Life Cycle Assessment of Greenhouse Gas Emission Equivalents

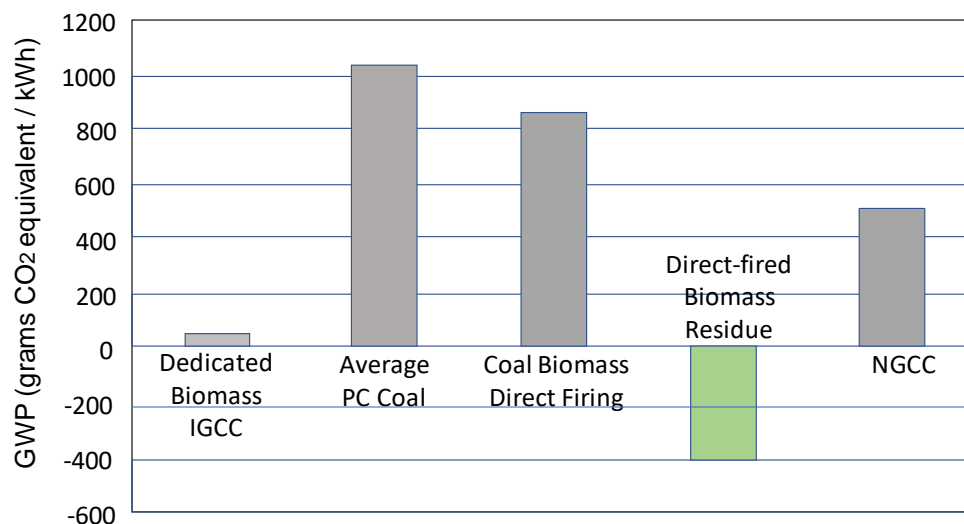
Bain <sup>[18]</sup> and Zaman <sup>[19]</sup> have provided life cycle assessments comparing landfill, incineration and gasification as primary technologies for treatment and disposal of MSW. Again, gasification ranked highest, overall, when considering the combined characteristics of conversion efficiency, cost per unit of power generated, and favorable environmental impact. Environmental advantages of thermal treatment of combustible waste, as compared to landfill, have been confirmed by the USEPA, which has concluded that landfills are an important source of fugitive methane gas <sup>[20]</sup>, which gas is some 25-fold more effective as a greenhouse gas than carbon dioxide (CO<sub>2</sub>).

Thermal treatment of MSW is a well proven technology for producing renewable energy, while greatly reducing the emission of methane and other greenhouse gases per unit mass of fuel, as well as a reducing the amount of waste going to landfills. This comparative advantage of gasification is maintained when compared to landfills with gas capture systems, with gasification producing only about 1 kg of CO<sub>2</sub> equivalent (CO<sub>2</sub>e) per kWh of generated power, while landfill produces approximately 2.75 kg/kWh, and incineration releases approximately 1.6 kg/kWh of energy generated. Air emissions from gasification are inherently lower than from incineration, whether calculated per ton of waste treated, or per MWh of energy generated. Gasification technology offers greater flexibility in facility design and layout and requires less heavy construction and civil work onsite than incineration, resulting in shorter construction times (and lower costs).

As a source of electrical power, thermal conversion of combustible waste is more effective in reducing GHGe emissions than pulverized coal combustion, coal biomass co-firing, or natural gas fired combustion turbine combined cycle. Data graphed in **Figure 21** shows that direct firing MSW biomass has the net effect of reducing GHGe emissions compared to placement in a landfill where anaerobic decomposition would produce methane that is more than 25 times as effective as CO<sub>2</sub> in trapping heat in the atmosphere.

Available data indicate that life cycle GHGe emissions from use of liquid transportation fuels derived from plastics will be less than those arising from the use of hydrocarbon fuels derived directly from crude oil <sup>[17]</sup>. Fuel quality and energy content are dependent on the type and condition of the plastic polymers converted <sup>[18]</sup>. According to an NREL "well to wheel" analysis of

the relative GHGe emissions from petroleum-based fuel production and use, properly designed and operated processes for production and use liquid fuels from plastics will produce less GHGe than the equivalent direct from petroleum fuel alternative.



**Figure 21.** Comparison of the GHGe contribution of power plants using different fuels

### Life Cycle Assessment of Plastics to Liquid Fuel Conversion Processes

A recent study published by Argonne National Laboratory indicates that a litre of ultralow sulphur diesel fuel derived from plastics requires 96% less energy to produce than a litre of diesel produced from crude oil. The same study estimates that use of waste plastics derived ULSD can reduce greenhouse gas emission equivalents by up to 14%.

### Economic and Commercial Advantages of an Integrated Approach

A desktop survey of capital expenditures (capex) for recently completed or planned gasification and incineration waste to energy plants shows costs range between approximately \$5.4 million and \$7.0 million per megawatt of generating capacity for plants in the 3000 ton per day / 100 MW range. The lower cost per MW of capacity was for an EPR gasification plant planned for North Las Vegas, NV, and the higher cost was for a recently completed mass burn waste incinerator in West Palm Beach FL.

Operational expenses per MW of generating capacity are lower for a mass burn incineration facility as compared with an RDF burn gasification plant. This is because preparation of the RDF for the gasification plant requires some manual sorting while little or no sorting of the waste is required for mass burn. However, gasification of RDF has an advantage when it comes

to air emissions because gasification, and especially gasification with flue gas recycle, is inherently cleaner than incineration. Furthermore, for a waste stream, the sorting involved in production of RDF leads to a cleaner fuel than would be charged into a bulk burn incinerator.

In an integrated waste to energy and plastics to Liquid Fuels facility such as described in this document, sorting of the incoming waste serves two purposes.

- (1) separation the combustible materials from the inerts and any hazardous wastes, with the resulting RDF is an improved fuel.
- (2) separation of fossil carbon material from biomass or cellulosic carbon materials.

The biomass carbon fraction of the waste stream is now comprised of renewable fuel, meaning that power generated from it can command a higher price in most jurisdictions. The fossil fuel fraction, comprised mostly of plastics, waste tires, and in some cases waste lubricants and heavy oil, can be chemically recycled to generate liquid and gas phase fuels, as well as a char that can be burned as fuel or sold as carbon black, depending on the feedstock. Integrating the conversion of the biomass and fossil fuel fractions in a single facility has financial advantages as shown in **Table 6**.

**Table 6** Estimated annual earnings per dollar of Capex for Five Conversion Technologies

Conversion Process	Annual Earnings / \$ of Capex (Est.)	IRR Range (20 Year)	Environmental Ranking vs Landfill
Incineration (Mass Burn)*	\$0.06*	N/A	(4)
Gasification (RDF)	\$0.13	8% to 16%	(3)
Gasification (Biomass Only)	\$0.12 - \$0.20	11 % -18%	(2)
Plastics to Liquid Fuels + Coke	\$ 0.60	>30%	(1)
Tires to Liquid Fuels + Char	No Data Available		(2)

\* Public utility – not for profit

## Summary

An integrated facility for the conversion of dry combustible solid waste, as described in this paper, offers several advantages in the management of MSW in the face of decreasing landfill capacity and increasing waste plastics volumes. Thermal treatment of biomass and fossil carbon waste, using the most environmentally responsible processes for each, can be accomplished in a manner that reduces environmental impact and increases total revenue from a given amount of waste.

The economics of thermal treatment of waste to generate electrical power varies greatly among jurisdictions. In much of western Europe, and in more densely populated in North America, the bulk of the revenue for waste to energy plants comes from tipping fees or gate fees. That is, the value of significant volume reduction and rendering inert combustible solid waste is more valuable than the power it produces.

Mid-distillate liquids of greatest value are those obtained from thermocatalytic cracking of fully saturated linear and branched chain aliphatic polymers, namely; HDPE, LDPE and PP. With the proper catalysts and process design, these polymers can be broken down into the same types of paraffins naphthenes and olephins that comprise the bulk of diesel fuels derived directly from petroleum. The additional cost involved sorting the various types of plastics from the incoming waste is more than compensated by the increased value of the liquid fuels obtained as compared to their value as a fuel for generating process steam or electricity. And in an integrated facility, waste tipping sorting and storage costs can be shared by the gasification and pyrolysis process lines.

In jurisdictions where the main revenue comes from rendering the waste inert and waste volume reduction, rather than electrical power generation, the inclusion of a plastics to liquids plant in the overall waste to energy facility can increase the amount of annual revenue earned per units of capex expenditure.

Economies are realized by having an integrated waste separation facility that separated biomass carbon from fossil carbon materials can each be processed in the most environmentally responsible manner. The biomass fraction is sent to the gasifiers while the plastics fraction is further separated to obtain the best polymer mix as feed for the pyrolysis plastics to liquids system.

As indicated in **Table 6**, the addition of a relatively small and inexpensive plastics pyrolysis plant to a larger waste to energy plant can allow the WtE plant to operate on renewable fuel while earning addition revenue that increases to overall plant IRR, making the overall enterprise more attractive to investors.

## References

1. Kimiko de Freytas-Tamura (2018) Plastics Pile Up as China Refuses to Take the West's Recycling, New York Times January 11, 2018  
<https://www.nytimes.com/2018/01/11/world/china-recyclables-ban.html>
2. Kaskey and Coe (2017) China's Blow to Recycling Boosts U.S.'s \$185 Billion Plastic Bet (Bloomberg Dec 5, 2017) <https://www.bloomberg.com/news/articles/2017-12-06/china-s-blow-to-recycling-boosts-u-s-s-185-billion-plastic-bet> USEPA (2009) Gasification and Renewable Energy <http://www.epa.gov/osw/hazard/wastemin/minimize/energyrec/renew.htm>
3. Münster, M (2009) Energy Systems Analysis of Waste to Energy Technologies by use of Energy PLAN, Danish Technical Research Counsel; ISBN 978-87-550-3719-9  
[http://orbit.dtu.dk/fedora/objects/orbit:81741/datastreams/file\\_4069900/content](http://orbit.dtu.dk/fedora/objects/orbit:81741/datastreams/file_4069900/content)
4. Nasrollah Hamidi, Fariba Tebyanian , Ruhullah Massoudi and Louis Whitesides (2013) Pyrolysis of Household Plastic Wastes British Journal of Applied Science & Technology 3(3): 417-439, 2013  
[http://www.journalrepository.org/media/journals/BJAST\\_5/2013/Mar/1363587430-Hamidi332012BJAST1984.pdf](http://www.journalrepository.org/media/journals/BJAST_5/2013/Mar/1363587430-Hamidi332012BJAST1984.pdf)
5. Benavides, PH et al., (2017) Life-cycle analysis of fuels from post-use non-recycled plastics, Fuel Vol 203 pg11-22.  
<https://www.sciencedirect.com/science/article/pii/S0016236117304775>
6. Rahimi, A and Gracia JM (2017) Chemical recycling of waste plastics for new materials production, *Nature Reviews Chemistry* **volume1**, Article number: 0046  
<https://www.nature.com/articles/s41570-017-0046>
7. Miskolczi, N, et al (2004) Thermal and thermo-catalytic degradation of high-density polyethylene waste Journal of Analytical and Applied Pyrolysis Volume 72, Issue 2, November 2004, Pages 235-242.  
<https://www.sciencedirect.com/science/article/pii/S0165237004000634>
8. Diesel Fuels Technical Review ( 2007) Chevron Corporation.  
<https://www.chevron.com/-/media/chevron/operations/documents/diesel-fuel-tech-review.pdf>
9. Goshen College, The Chemistry of Biodiesel: Differences Between Biodiesel, Diesel and Vegetable Oil <https://www.goshen.edu/academics/chemistry/biodiesel/chemistry-of/>
10. Yue, L, et al., (2016) Impacts of hydrogen to carbon ratio (H/C) on fundamental properties and supercritical cracking performance of hydrocarbon fuels. Chemical Engineering Journal Vol. 283, 1216-1223  
<https://www.sciencedirect.com/science/article/pii/S1385894715011638>

11. Syamsiro, M. et al., (2014) Fuel Oil Production from Municipal Plastic Wastes in Sequential Pyrolysis and Catalytic Reforming Reactors, *Energy Procedia* 47 ( 2014 ) 180 – 188
12. Merve Sogancioglu (2017) A Comparative Study on Waste Plastics Pyrolysis Liquid Products Quantity and Energy Recovery Potential *Energy Procedia* Volume 118, August 2017, Pages 221-226  
<https://www.sciencedirect.com/science/article/pii/S1876610217325468>
13. Wang and Bucanon (2019) Millions of tons of the world's plastic waste could be turned into clean fuels, other products through chemical conversion.  
<https://www.purdue.edu/newsroom/releases/2019/Q1/millions-of-tons-of-the-worlds-plastic-waste-could-be-turned-into-clean-fuels,-other-products-through-chemical-conversion.html>
14. Behrendt, et al (2008) Direct Liquefaction of Biomass, **Chemical Engineering and Technology** Vol 31; 5 pp 667-677  
<https://onlinelibrary.wiley.com/doi/pdf/10.1002/ceat.200800077>
15. Seshasayee and Savage (2019) Study of Hydrothermal Liquefaction as a Process for Utilizing Municipal Solid Waste Without Separation <https://drawdown.psu.edu/poster/study-hydrothermal-liquefaction-process-utilizing-municipal-solid-waste-without-separation>
16. Stantec (2011): Waste to Energy: A Technical Review of Municipal Solid Waste Thermal Treatment Practices Final Report (2011) Environmental Quality Branch Victoria BC  
<http://www.env.gov.bc.ca/epd/mun-waste/reports/pdf/BCMOE-WTE-Emissions-final.pdf>
17. BPA (2009) Evaluation of Emissions from Thermal Conversion Technologies Processing Municipal Solid Waste and Biomass: Final Report (2009) Bioenergy Producers Association <http://socalconversion.org/pdfs/UCR Emissions Report 62109.pdf>
18. Bain, R.L., et al., Biopower Technical Assessment: State of the Industry and Technology. 2003, National Renewable Energy Laboratory.  
<https://www.nrel.gov/docs/fy03osti/33502.pdf>
19. Zaman, A U (2010) Comparative study of municipal solid waste treatment technologies using life cycle assessment method *Int. J. Environ. Sci. Tech.*, 7 (2), 225-234, Spring 2010 ISSN: 1735-1472  
<http://link.springer.com/article/10.1007%2FBF03326132#page-1>
20. Thorneloe, SA (2012) U.S. Trends in Solid Waste Management and GHG Emissions Health and Environmental Concerns for Landfills ,Berlin Germany  
[http://www.umweltbundesamt.de/sites/default/files/medien/421/dokumente/us\\_epa\\_swm\\_and\\_ghg\\_emission.pdf](http://www.umweltbundesamt.de/sites/default/files/medien/421/dokumente/us_epa_swm_and_ghg_emission.pdf)