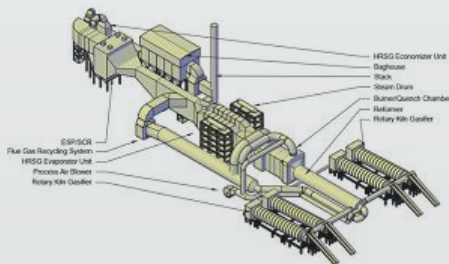


Comparative Emissions from Baseload Renewable Energy Sources

Bary Wilson, Ph.D.

November 2018



EnviroPower Renewable, Inc.
 7301A Palmetto Parkway Rd.
 Suite 206B Boca Raton, FL 33433
www.eprenewable.com

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This document is provided in response to a request from LAPWD for a comparison of the relative greenhouse gas equivalent (GHGe) emissions per kWh of electrical energy produced by currently available renewable baseload generation technologies. In addition to GHGe, consideration is also given to relative levels of NO_x, SO_x and particulate emissions, since these pollutants are important determinants of overall air quality. Where data are available, these comparisons are made in terms of a life cycle assessments (LCA).

Nuclear, hydro, and closed loop binary cycle geothermal are not considered in this comparison. While these baseload plants can have significant environmental impacts if not properly designed and operated, they are not significant sources of GHGe, NO_x, SO_x, or particulate matter (PM). Open loop geothermal can be a significant source of GHGe and other pollutant gasses. However, the authors could find no reference to commercial open loop geothermal power generation in California. Solar, wind and tidal turbine generation systems, while considered renewable power sources, are not considered because they are not capable of baseload generation. Digester biogas is unlikely to constitute a significant energy source and is not considered specifically in this document.

As described in a recent report ^[1] published by California Air Resources Board, energy generated from biomass makes up approximately 19% of California's instate renewable power generation and about 2% of California's overall power mix. At the time of the report (2015), approximately 550 MW was generated by direct combustion of woody biomass and approximately 280 MW by combustion of recovered landfill gas. Combustion of wastewater treatment biogas accounted for some 75 MW. Municipal solid waste (MSW), typically between 60% and 70% biomass, is the second largest source of biomass in California. Despite numerous policy recommendations to better utilize this renewable resource, landfill placement remains the primary means of disposal for MSW.

Renewable baseload generation technologies considered in this document include:

- Landfill gas recovery and combustion
- Pyrolysis of biomass,
- Combustion of biomass (incineration of MSW biomass),
- Conventional biomass gasification compared to EPR gasification of biomass recovered from source separated commercial waste and construction and demolition debris

Thermal Conversion of Carbonaceous Solid Waste

Given that the above are all thermal processes for the conversion of carbonaceous materials, they can be expected to produce nominally the same amount of carbon dioxide (CO₂) for a given amount of carbon in the fuel once all of the gasses, liquids and chars produced are fully oxidized and converted to energy. Therefore, the difference in the respective environmental impacts of these thermal conversion processes is largely determined by their respective air emissions other than CO₂. Air emissions avoided by the use of a given technology, as compared to alternatives, should also be considered. For example, thermal conversion of a ton green waste biomass results in a much lower release of GHGe to the environment than does placement of this same ton of biomass in a landfill, where it would eventually be anaerobically converted to CO₂ and methane (CH₄).

As shown in **Figure 1** below, 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 CO₂, 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. **Figure 1** shows the proportion of GHGe that is due to non-collected (fugitive) emissions from landfill.

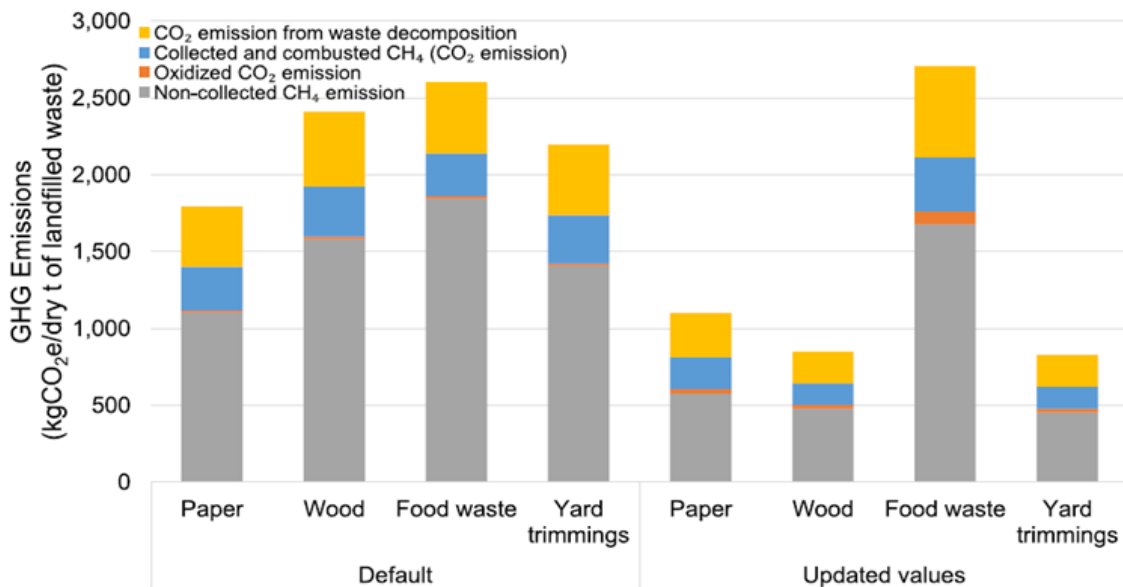


Figure. 1 The fates of carbon from four types of landfilled wastes using default and updated parametric values for fraction of degradable materials to be decomposed and the oxidation factor of CH₄ from landfills. (From Lee, Han and Wang, 2017)

Landfill Gas Recovery and Combustion

Emissions associated with landfill gas recovery and conversion for the various components that make up MSW (paper wood, etc.) are represented by **Figure 1**. An LCA for this technology shows that landfills are an important source of GHG, as recognized by the USEPA and other regulatory agencies [3,7]. Biomass typically constitutes between 60% and 70% of municipal solid waste. The California Bioenergy Interagency Working Group recently estimated that approximately 38 million dry tons of biomass goes to landfill each year in California as municipal solid waste. As reproduced below, California policy makers have recommended the diversion of biomass waste from landfills and its use as a fuel for power generation.

Landfill Diversion. The biomass component of municipal solid waste totals approximately 38MDT per year. Biomass conversion technologies have the potential to return a significant portion of this post-recycled fraction of the waste stream to an economic stream in the form of power, fuels, and chemicals. Development of these new industries will enable California not only to meet but substantially exceed its current 50 percent recycling goal while reducing pollution and fostering economic growth.

Figure 2 below illustrates the various means by which biomass in landfills contributes to GHGe emissions. In addition to CO₂ and CH₄, landfill gas emissions include air pollutants such as hydrogen sulfide, ammonia, and several mercaptans that give rise to nuisance odors and are hazards to the environment and human health.

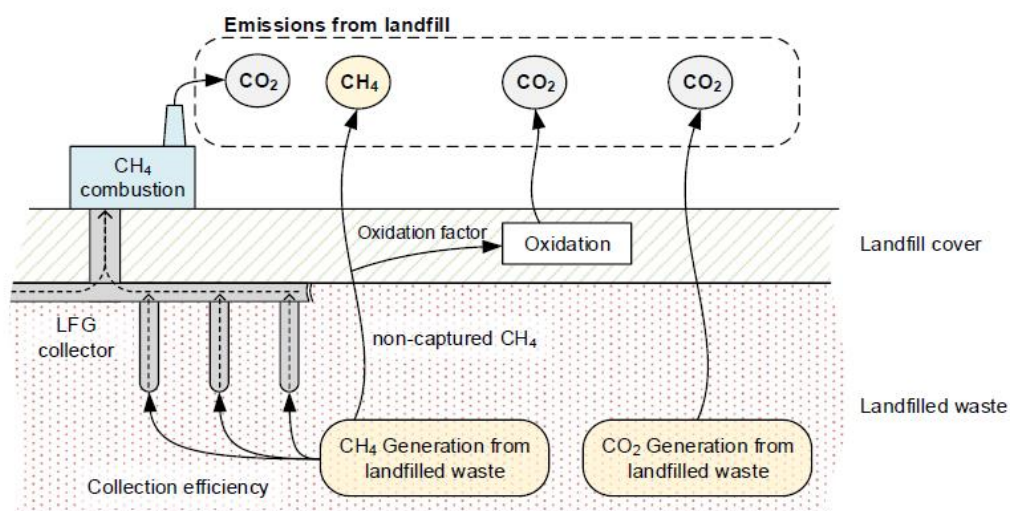


Figure 2. Fate of gasses generated from biomass placed in landfills (Lee, Han and Wang [3])

As depicted in **Figure 2**, landfill gas is collected from wells drilled into the compacted landfill material after the cell is closed and the final cover is installed. This gas is cleaned by removing the contaminant gasses including hydrogen sulfide with the recovery of elemental sulfur. The cleaned gas, comprised mainly of methane and CO₂, is used to fire reciprocating engine, or small gas turbine, gensets. **Table 1** below compares the conversion efficiency of direct thermal conversion of MSW biomass to electricity as compared to recovery and conversion of landfill gas.

Table 1. Comparison of Electricity Generated by Direct Conversion of MSW vs Landfill of MSW (From [4])

	Total Electricity Generated from 166 MM Tons of MSW in (TWh)	Total Power, GW	Electricity Generated from 1 ton of MSW (kWh/Ton)
Thermal Waste to Energy Conversion	78-160	9.7 - 19	470-930
Landfill Gas to Energy	7-14	.085- 1.8	41-85

As listed on a State of California Biomass to Energy website, the advantages of direct conversion of the biomass component of MSW to energy are as follows.

- The supply of biomass is renewable, meaning it will not run out.
- Electricity produced by biomass reduces the threat of global climate change.
- Using biomass waste eliminates the need to place it in landfills.
- Clearing biomass from wooded areas helps prevent forest fires.
- Using by-product methane gases to produce electricity eliminates odor and reduces air pollution in surrounding areas

Pyrolysis of Biomass

Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the heated material. In pyrolysis, lower process temperature and longer vapor residence times favor the production of a char material. High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapor residence time are optimum for producing liquids.

Pyrolysis of biomass, or dried combustible components of MSW, is carried out in a low- or no-oxygen environment at relatively low temperatures (approximately 400 to 800 degrees F), depending on the fuel material. The pyrolysis of wood, a common feed stock for this process, for example, starts at 390–570 °F (200–300 °C). At these reaction temperatures, the thermal energy available is not sufficient to completely break down the constituents (mainly lignin) to carbon monoxide and hydrogen fuel gas.

Upon cooling, much of the material that leaves the reactor in the gas phase condenses to form a liquid. Lighter gas phase components that do not re-condense, such as H₂, CO, CH₄ and C₂H₅, are commonly combusted to provide heat to the main reaction chamber. At pyrolysis temperatures much of the carbon in the fuel does not react and leaves the process as a char. **Table 2** indicates the product distribution obtained from different pyrolysis conditions of temperature and residence time.

Table 2. Liquid, char and gas production as a function of pyrolysis temperature and residence time

Process	Conditions	Liquid	Char	Gas
Fast Pyrolysis	Moderate temperature, short residence time, especially for the vapor	75%	12%	13%
Carbonization	Low temperature, very long residence time	30%	35%	35%
Gasification	High Temperature, long residence times	5%	10%	85%

Of primary interest in pyrolysis of biomass is the production of fuel gas and liquid fuels with the char being a by-product that is used in some processes as a source of preheat for the main reactions. Elemental composition and physical characteristics of an oil recovered from fast pyrolysis of wood is shown below in **Table 3**.

Table 3. Characteristics of pyrolysis oil derived from wood.

Elemental Composition	C ₂ H ₅ O ₂
Density	1,150 - 1,250 kg/m ³
Higher Heating Value	17-20 GJ/m ³
Water Content	15-30wt.%
Viscosity	25-1000 cP
Ash Content	< 0.1%

Pyrolysis processes are mainly small scale and oriented to the production of liquid fuels. Their direct contribution to electrical power generation is unlikely to be significant. A comparison of the air emissions from a number pyrolysis processes is provided in reference [8]. According to an NREL "well to wheel" analysis of the relative GHGe effect of petroleum-based fuel production, it is likely that properly designed and operated pyrolysis processes for liquid fuels from biomass will produce less GHGe than the fossil fuel-based alternative.

Direct Thermal Conversion of Biomass

Policy on landfilling of biomass must also be taken into account when considering the LCA for thermal conversion technologies such as incineration and gasification. As shown in **Figure 3** below, Bain et al.^[6] from the National Renewable Energy Laboratory carried out an LCA in which they showed that direct thermal conversion resulted in a substantial negative GHGe value due to the alternative fate of this material through anaerobic decomposition in a landfill producing methane gas.

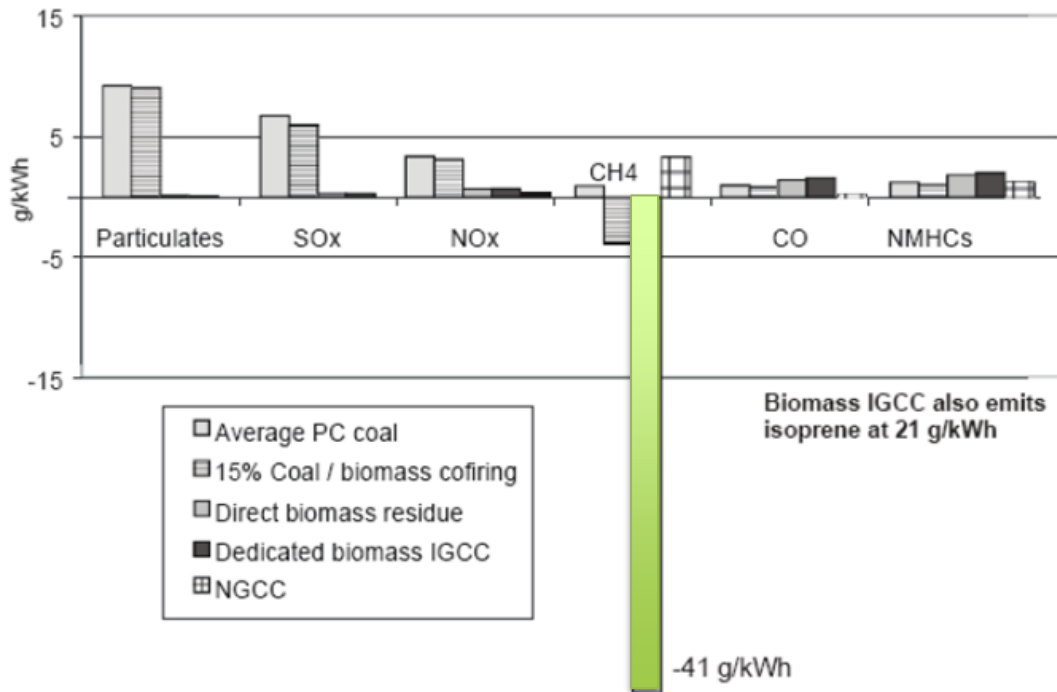


Figure 3. Life cycle pollutant emissions for several different scenarios of electricity generation (Bain et al., 2003)

In the early 1990s, California had an installed capacity of more than 800 MW of biomass fired generation. However, as federal government price supports for biomass expired and natural gas became less expensive as a fuel for power generation, many of the contracts for power from the biomass plants were not renewed upon expiration. For these reasons, as well as inadequate tipping fees, by 2015 biomass fired generation capacity had dropped well below 600 MW. Unlike in Western Europe, for example, where tipping fees are adjusted to support a policy of steep reductions in organic materials to landfill, tipping fees in the US are relatively low and do not constitute a significant incentive for diversion.

Direct combustion of biomass is carried out primarily in traveling grate stoker boilers. Newer plants use circulating fluidized bed boilers. As described above, the GHG emissions from these facilities, as a function of GHGe units per kWh of energy generated, depends largely on the design and operation of the boiler and the pollution control equipment installed at the plant. As shown in **Figure 4** below, a life cycle assessment comparison undertaken by Bain, et al. [6] comparing GHGe of pulverized coal, coal/biomass, natural gas combined cycle, and direct fired biomass residue conversion showed that direct thermal conversion of biomass actually reduces GHGe compared to the alternative. Note that the direct fired biomass residue option represents a substantial reduction in GHGe as compared to natural gas fired combine cycle (NGCC) system.

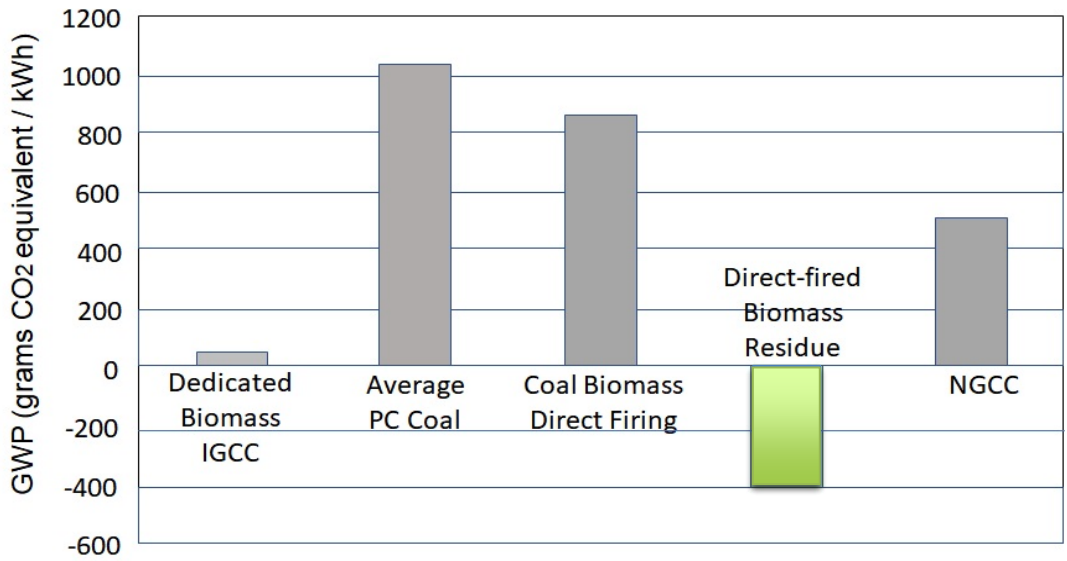


Figure 4 Life cycle GHG emissions for several different scenarios of electricity generation (from Bain et al., 2003 [6])

Conventional Gasification Compared to EPR Gasification

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 [5].

The significant differences between gasification and incineration are illustrated in **Figure 5** below. 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.

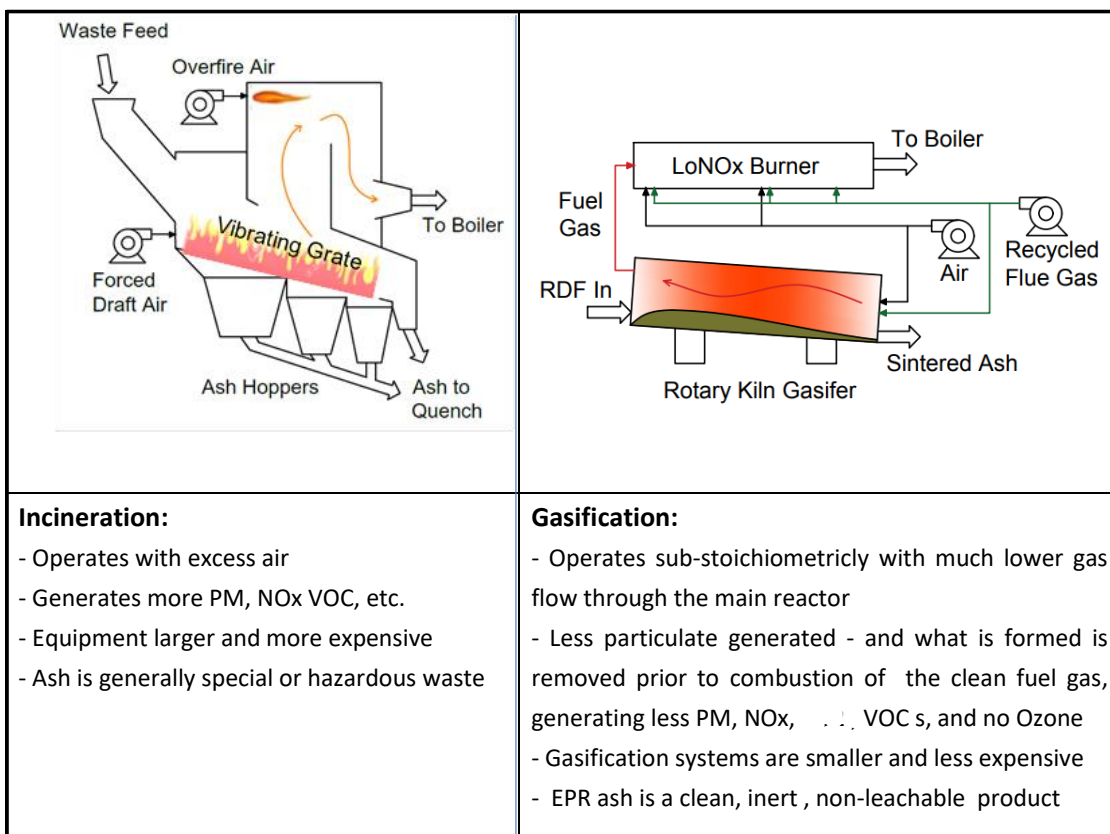


Figure 5 comparison of gasification and incineration processes for thermal conversion of biomass

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.

Rigorous comparison of GHG emissions and other pollutants would require that the air permits and publicly available stack emission records from operating plants be compared and then normalized for fuel composition and other factors. For comparisons of emissions from conventional waste to energy gasification to the EPR LoNOx rotary kiln design, **Table 4** lists the permitted emission from the EPI gasification facility in Plainview, CT, and the EPR 50 MW gasification line (which has been permitted as a synthetic minor source) in Nevada.

Table 4. Comparison of permitted emissions for a conventional gasifier system and an EPR LoNOx system of similar scale and similar fuel mix

Criteria Pollutant	Permitted Tons per Year per MWe of Generating Capacity	
	Plainville (EPI)	Las Vegas (EPR)
PM ₁₀	1.2	0.4
NO _x	4.6	1.8
SO _x	2.2	2.0
VOC	0.7	0.3
CO	6.4	0.8
Pb	0.009	0.00018

Emissions are listed based on permitted tons per year per MWe of generating capacity. The EPI facility is permitted to process some 1,300 tons per day and generate 37.5 MW net to the grid. The EPR facility under development in Nevada is also permitted to process some 1,300 tons of waste per day waste and will generate 42.5 MW net to the grid. Note that emissions of most criteria pollutants are substantially lower for the EPR plant, which will generate approximately 12% more energy than the EPI facility.

Summary and Comments

As described above, the total amount of CO₂ resulting from the complete oxidation of the carbon in biomass is essentially independent of the process by which the total oxidation (combustion) occurred. However, the resulting GHGe per unit of electrical energy generated is dependent on the efficiency of the process, and gasification of MSW biomass is generally considered more efficient than incineration. As illustrated by the landfill gas example, as well as the liquid biofuels vs petroleum derived fuels example, net GHGe should be determined by considering an LCA for the process in question.

Figure 6 below provides a comparison of the relative GHGe per unit of energy generated for thermal conversion of MSW by landfill gas recovery, incineration and conventional gasification. While the data in **Figure 6** are a compilation from 2012, these relative values remain valid even though both incineration and gasification technologies have since improved in environmental performance. Although these data reflect the conversion of MSW comprised of both contemporary and fossil carbon combustible materials, it is safe to assume that the same relative GHGe would result from thermal conversion of contemporary cellulosic (non-fossil) carbon only.

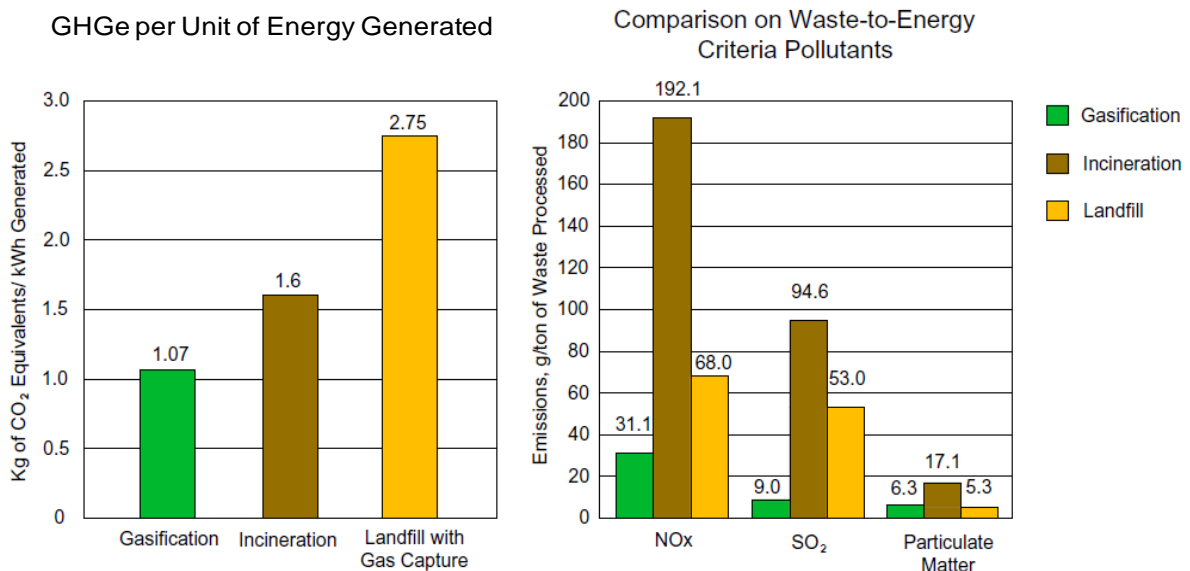


Figure 6 (L) GHGe per kWh of generation; (R) comparison of relative emissions of NO_x, SO_x and particulate matter for three thermal conversion processes

The main fossil carbon-derived constituents of MSW are plastics, which generate very little, if any ash and, with the exception of ABS and PVC, generally do not contain heteroatoms such as sulfur and chlorine. **Figure 6 (L)** shows the GHGe per unit of energy generated for three methods of converting municipal solid waste to energy. Figure 6 (R) provides a comparison of NO_x, SO_x and particulate emissions for the three thermal conversion processes.

Comments:

A study ^[2] by the California Bioenergy Interagency Working Group, which included the California Energy Commission and the Air Resources Board, recommended that the State, "Target the development of 1,500 MW of new biopower capacity by 2020 so that biopower can continue to provide a 20 percent share of in-state renewable electric power as part of the state's accelerated RPS."

1. EPRLV's proposed 100MW renewable energy baseload plant* allows for a utility to secure a long-term renewable baseload capacity while reducing GHGe compared to the current preferred approach of landfilling.
2. The EPRLV solution will also provide energy a cost advantage to historical geothermal energy.
3. The anticipated unit cost (per kWh) of electricity from EPRLV is competitive with solar plus battery storage without a degradation of output over time. In addition, there is no need to plan for long term hazardous waste handling of batteries and solar panels on unit replacement.
4. EPRLV baseload power represents a consistent capacity factor without having to scallop other sources to meet consumer load profiles, which can be a burden on the transmission grid.

* This plant has been pre-certified as renewable by the California Energy Commission and is currently being permitted as a synthetic minor stationary source of air emissions by the Clark County Department of Air Quality

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This document is provided, at the request of LADWP, as an addendum to the April 19, 2018 presentation by EPR regarding a 100 MW Renewable Energy Gasification Project in North Las Vegas, NV.

khulbert@eprenewable.com

(703) 668-0486 (office)

(703) 725-7687 (mobile)