Waste-to-Energy in California:
Technology, Issues and Context

Do waste-to-energy technologies have a role in California's path
to a cleaner environment?

A report to the California Council on Science and Technology
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1. Summary

1.1 Purpose of this Report

This report serves as a starting point for discussions concerning the conversion of post-recycled urban-derived biomass and municipal waste to energy. It is not intended to be an all-inclusive review. There is controversy regarding the technologies, especially eligibility of thermal systems such as gasification for the State's renewable portfolio standard (RPS) (see Appendix). This prompted the Governor's Office to ask the California Council on Science and Technology (CCST) to undertake a review of the operation, technological, and environmental performance of conversion technologies, with special focus on gasification, in order to answer the following questions:

1. Can these technologies be safely deployed in California? Is there adequate information relating to criteria and hazardous air emissions and other potential pollutant discharges from conversion technologies to be able to determine the suitability of these technologies within the California waste management sector?

2. Can the deployment of these technologies be done in such a way as to support and enhance the State's recycling efforts beyond the current estimated 60-65% diversion rate? What changes to the regulatory and fiscal policies may be needed in order to achieve this?

3. If it is determined that waste-to-energy technologies can meet California environmental standards and can be done in such a way as to support and enhance the State's recycling goals, what State policy changes and incentives are needed to develop this alternative?

1.2 Findings

- Waste-to-energy technologies could have positive environmental impacts in California.[1]

- Converting municipal waste to energy is controversial. Both sides in the debate have substantial and valid positions. The possible positive and negative effects of waste-to-energy include:

Table 1: Benefits and risks of waste-to-energy systems.

Possible Benefits	Possible Negative Impacts
Decreased landfill burden	Disincentive to waste reduction and recycling programs
Decreased greenhouse gas emissions through offset of fossil fuels	Increased air and water impacts with a disproportionate effect on already stressed urban areas
Reliable, local, low-carbon electricity that could fill response gaps of intermittent renewables like wind and solar	High costs may force scaling and lifetime of facilities that is contradictory to overall conservation goals – potentially exacerbated if companies receive renewable credits
Local energy source (fuels or electricity)	Financial risk for communities if technology is unreliable

- The actual impacts of any waste-to-energy system are specific to that system. Changes in location, waste composition, equipment type and configuration, operating conditions, and post-generation control techniques can all influence the overall environmental and economic performance of the system. Any of these factors can "change the sign" of the outcomes, causing a system to have net positive or negative impacts.

- Life-cycle analysis (LCA) of waste management options is a valuable tool for decision making; however, comparisons and generalizations must be carefully framed as there is insufficient agreement in the life-cycle analysis literature for MSW energy technologies. This is largely due to variation in process- and site-specific variables including equipment, waste composition, and geology; disharmony in methodological approaches including system boundary designation, allocation techniques, and offset credits; and lack of verified independent data for newer technologies.

- There are conversion technologies that will meet California's environmental quality standards. The California Environmental Quality Act requires that each project be scrutinized and evaluated in the permitting process to ensure that land use, air and

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[1] These finding are in general agreement with the California Energy Commission's 2011 Bioenergy Action Plan. A Report to the Bioenergy Interagency Working Group: 1-87.

water quality standards will be met; however, there are always operational uncertainties with new technologies and no guarantee that a system implemented successfully in one location will perform equally well in another.

- Implementation of waste-to-energy systems are expensive and require additional economic and/or policy incentives if such systems are desired. These policy incentives must be carefully framed to avoid unwanted direct or indirect effects.
- The implementation of waste-to-energy systems creates additional markets for municipal wastes, which can either interfere or act synergistically with recycle and reuse efforts. State law currently requires that "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." Further clarification through the regulatory process could better elaborate waste reduction and recycling goals.
- The bioenergy interagency working group has looked extensively at this issue and plays a key role in assessing technological, political, and economic factors related to biomass including organic municipal waste.

1.3 Recommendations

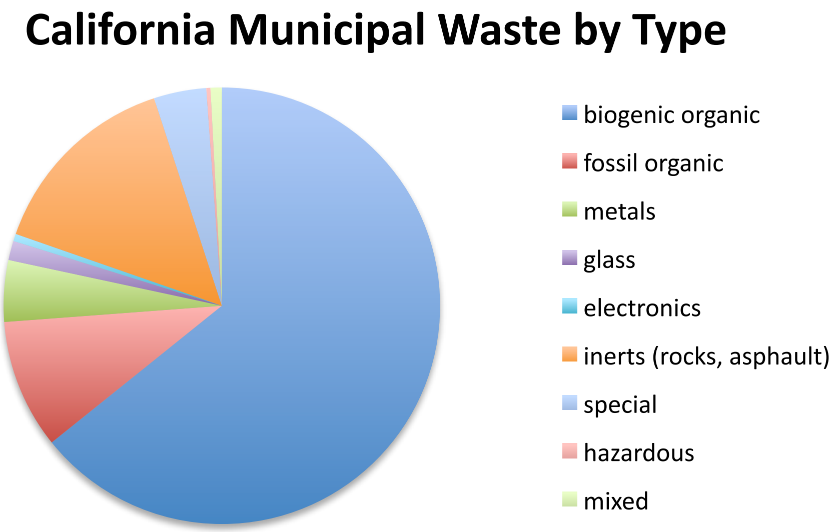
- All parties will benefit from updated tracking of real emissions and performance data from operating waste-to-energy systems. Care must be taken in interpreting transferability of both good and poor performers to California regional waste scenarios.
- All parties would benefit from development of a regionally specific optimization model that includes all waste management options to assist communities with waste management decisions. The model should incorporate standardized life-cycle analysis using site-specific data where possible, coupled with an economic assessment including markets for recycled and recovered materials. The model should allow prioritization of policy goals including emissions control, landfill diversion, costs, etc.
- All parties will benefit from continued open and transparent dialogue surrounding waste to energy systems. Research and education in this area is a continuing need.

2. Background

2.1 Municipal Waste in California

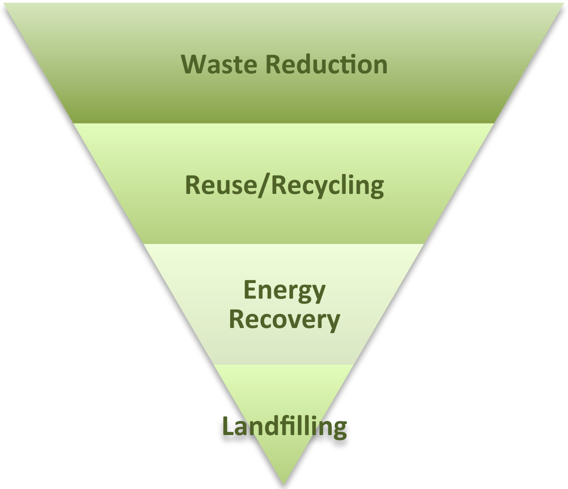
In 2007, nearly 40 million tons of municipal solid waste was handled by disposal companies. The typical composition of waste generated from commercial and residential activities is shown in Figure 1.

Figure 1. California Municipal Waste in 2007[2]. Biogenic carbon accounts for 60% of total waste.



Through a policy of integrated waste management, the State has embraced a waste management hierarchy that emphasizes diversion of waste from landfill through waste reduction and reuse/recycle programs. This is in general alignment with the hierarchy embraced by the US EPA and EU (Figure 2)[3]; however, California has been reticent to endorse substantial waste-to-energy, primarily due to opposition to conventional incineration. This opposition is based on concerns about emissions. Many of the high-volume waste producing communities are in

Figure 2. General Waste Management Hierarchy



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[2] California Integrated Waste Management Board (2009). "California 2008 Statewide Waste Characterization Study." 1-172.. Organic material contains carbon and includes renewable compounds that are biological in origin (biogenic) such as food, wood, paper and bioplastics, as well as non-renewable fossil-derived organic compounds such as conventional plastics.

[3] http://www.epa.gov/epawaste/nonhaz/municipal/wte/nonhaz.htm

extreme non-attainment areas for air quality, complicating siting and permitting.

Municipal solid waste (MSW) represents 40% of the residual biomass that could be used to generate biofuels or renewable biomass electricity within the state.[4] Organic materials represent 7 of the top 10 most prevalent waste types – over 60% of total non-hazardous waste in California[2] (Table 2). Overall, California municipal waste in 2007 contained 29.3 million tons of organic material including 6.8 million tons of paper products, 3.8 million tons of plastic, 5.8 millions tons of lumber[5], and 12.9 million tons of other organic material (e.g. food scraps, yard trimmings, textiles, woody waste, etc.). While some of this material is recycled, an estimated 19 million dry tons of organic municipal waste are landfilled each year.[6]

Table 2. Top ten most prevalent items in California's waste disposal system.[2] Seven of the top ten are organic (bold type).

Rank	Material	Percent Total Waste	Estimated Tons
1	**Food**	**15.5%**	**6,158,120**
2	**Lumber**	**14.5%**	**5,765,482**
3	Remainder/Composite Inerts and Other	5.5%	2,175,322
4	**Remainder/ Composite Paper**	**5.2%**	**2,056,546**
5	**Uncoated Corrugated Cardboard**	**4.8%**	**1,905,897**
6	**Remainder/ Composite Organic**	**4.3%**	**1,719,743**
7	**Leaves and Grass**	**3.8%**	**1,512,832**
8	Bulky Items	3.5%	1,393,091
9	**Carpet**	**3.2%**	**1,285,473**
10	Rock, Soil and Fines	3.2%	1,259,308

When employed efficiently, recycling and composting save energy by displacing the need for virgin or fossil-derived materials; however, in some cases, these recovery methods can have higher environmental impacts than landfill or energy recovery (see section 3). Even the best

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[4] Jenkins, B. M. (2005). Biomass in California: Challenges, opportunities, and potentials for sustainable development. PIER Collaborative Report California Biomass Collaborative, California Energy Commission..

[5] Lumber is classed as "Inerts and Others" along with asphalt and rocks by CIWMB. This class was formerly "Construction and Demolition".

[6] California Energy Commission (2011). "2011 Bioenergy Action Plan." Report to the Bioenergy Interagency Working Group: 1-87. 20 million tons at conversion rate of 20-80 gge per ton or 0.7 GW

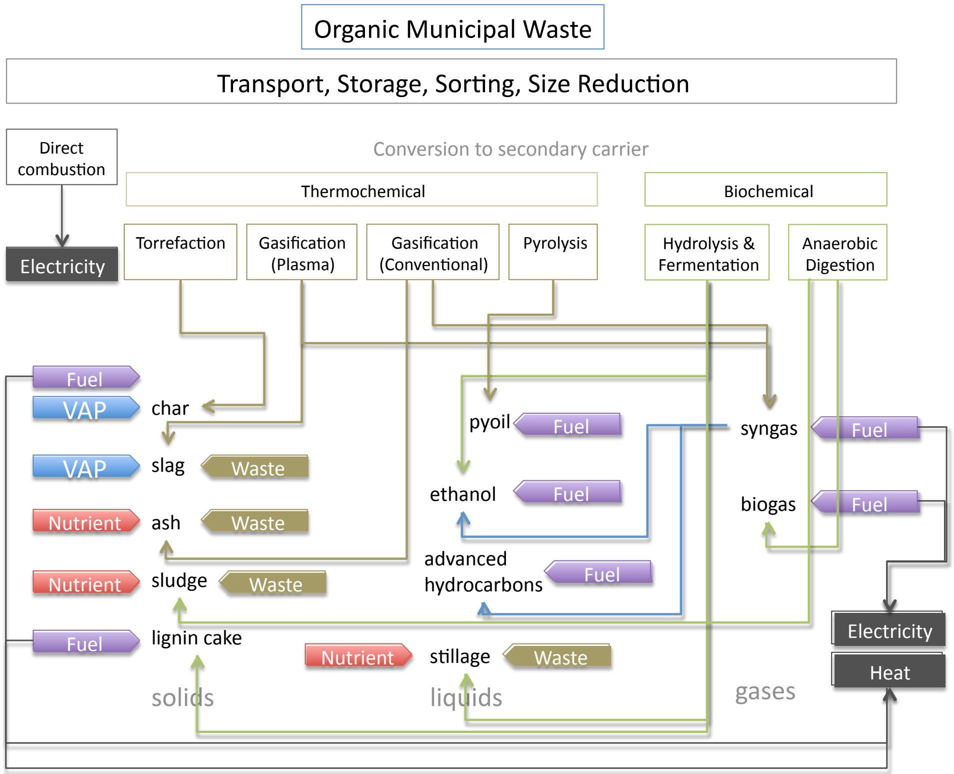
practices of recycling leave residual biomass that is suitable for energy production but is currently landfilled.

Some organic materials such as lumber and paper can be recycled at rates of 60 to 75%[7]. Other materials such as food scraps and yard trimmings have high composting efficiencies, which enables nutrient recycling and soil improvement. Up to 30% of the organic material in California MSW could be compostable; however, the limited market for this material has ironically prompted some communities to sell it to landfills for use as alternative daily cover. Integrating energy recovery with material recovery would allow processors to offset internal operating costs and respond nimbly and both markets, increasing actual diversion from landfill. Unfortunately, the current policies surrounding MSW disposition and especially waste-to-energy in California, severely inhibit such integration.

2.2 Waste-to-Energy Technologies

Organic materials have embedded energy that can be released with variable efficiency using two basic systems. Biological systems take advantage of natural processes to degrade biomass. Typically this is accomplished under mild conditions, although some chemical

Figure 3.Material flows in waste-to-energy technologies[8]



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[7] Taylor Recycling (http://www.taylorrecycling.com/); Friends of the Earth UK (http://www.foe.co.uk/resource/briefings/paper_recycling.html). In this paper, the thermal process of combustion is considered separately from thermochemical processes – torrefaction, pyrolysis and gasification.

pretreatment may be required. Thermochemical systems use heat to breakdown biomass into liquid or gaseous components (Figure 3).[8]

Feedstock composition may be the single most important factor in safe and reliable operation of a waste-to-energy facility. While systems can be optimized for any particular feedstock composition, there are some general rules regarding appropriateness of technologies for particular waste types (Table 3). For example, wastes that are high in moisture content (e.g. food waste) generally perform poorly in thermal systems because a large portion of the energy input is wasted in driving off water; feedstocks that are high in chlorine (e.g. PVC plastics, and as salt in food wastes or agricultural residues) are more likely to produce dioxins in thermal processes; wastes that are high in cellulose and lignin (textiles, paper and wood) have very long residence times in anaerobic digestion systems.

Table 3. Matching Organic Waste Feedstocks to Appropriate Technologies.

Feedstock	Landfill	Compost	Anaerobic Digestion	Hydrolysis	Incineration	Pyrolysis	Gasification
Food	░	░	░	░	▒	▒	▒
Grass/Leaves	░	░	░	░	▒	▒	▒
Paper/Cardboard	░	░	░	░	░	░	░
Wood	░	░	▒	░	░	░	░
Textiles	░	▒	▒	░	░	░	░
Manure	░	▒	░	▒	▒	▒	▒
Bioplastics	░	▓	▓	▓	░	░	░

Acceptable	Problematic*	Not Suitable
░	▒	▓

*Not energy efficient or requires additional pretreatment beyond particle size reduction

2.2.1 Biological Systems

Anaerobic digestion involves degradation of organic material, typically as a wet slurry, by mixtures of bacteria in the absence of oxygen to yield biogas, a mixture of CO_2, methane, and hydrogen. Biogas can be directly combusted for electricity or further treated to isolate the biomethane which can replace natural gas. The process also yields an undigested organic sludge that can be used for fertilizer or dried and used in thermal energy recovery. The acceptable uses of the sludge depend largely on the feedstock composition. Mixed municipal waste often contains toxic materials such a mercury, cadmium, and lead, or high salt concentrations that can restrict suitability as a fertilizer. Some materials are more easily digested and yield higher biogas than others (Table 4).

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[8] Adapted from Bosmans, A. and L. Helsen (2010). "Energy from Waste: Review of Thermochemical Technologies for Refuse Derived Fuel (RDF) Treatment." Proceedings of the Third International Symposium on Energy from Biomass and Waste Venice, Italy; 8-Nov-2010: 1-34.

In hydrolysis and fermentation systems, biomass is pretreated with any combination of heat, acid or base, and hydrolytic enzymes to reduce it to components such as sugars, lipids, and amino acids. The digested material can then be biologically converted through fermentation to molecules such as ethanol or other metabolic byproducts.

Table 4. Digestibility of various materials by anaerobic digestion and biogas production (100 day residence time).[9]

Material	Dry matter (% wet weight)	Loss on ignition (% dry weight)	Mean biogas (L/kg)	Estimated waste C mineralized (%)	Biogas calculated as received (L/kg wet wt)
Cellulose	96.5	99.7	136	16.9	131
Compost	64.0	30.8	24	4	5
Corrugated card	93.5	91.0	320	37.8	272
Cotton	98.0	99.6	26	2.6	25
Grass	18.9	85.0	225	33.1	36
Meat	22.9	92.0	633	61.7	133
Diapers	97.4	88.6	278	38.5	240
Newspaper	93.5	92.8	76	8.5	66
Twigs	63.8	96.0	93	10	57
Vegetables	12.8	93.8	312	40.6	37
Wool	95.2	89.5	21	3.4	18

Nutrients can be recovered in the stillage liquid or solids, depending on the feedstock. Contamination by heavy metals may negatively impact the conversion process and usefulness of any byproducts. By their nature, biological systems are limited to materials that can be metabolized by microorganisms. Tuning the system to fit the feedstock is likely to be required to achieve maximum efficiency.

2.2.2 Thermochemical Systems

Incineration, gasification, and pyrolysis form a continuum of thermal treatments where variation in heat and oxygen determines how the biomass is broken down to constituent molecules. Whereas incineration is direct oxidative combustion of waste using excess air or oxygen, thermochemical conversion systems such as pyrolysis and gasification (both conventional and plasma) occur with zero and low levels of oxygen, respectively. Thus incineration results in the formation of oxygen-containing products (oxides) such as carbon dioxide, carbon monoxide, nitrous oxides, and in some cases, dioxins. Because thermochemical processes are conducted in oxygen-poor environments, they form far fewer oxides and there is greater opportunity to control the chemistry in gas formation and in

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[9] Burnley, S., R. Phillips, et al. (2011). "Energy implications of the thermal recovery of biodegradable municipal waste materials in the United Kingdom." Waste Management 31: 1949-1959.

subsequent steps such as combustion to generate electricity or catalysis to produce liquid fuels. Typical products and conditions are shown in Table 5.

Thermochemical systems can handle a wide variety of feedstocks including mixed waste; however, tuning conversion efficiency to variable feedstocks is very difficult and cleaning of the gas for chemical catalysis to fuels or other chemicals is very expensive. If the quality and composition of the syngas are important, sorting of feedstocks into appropriate materials is needed. Waste composition and reaction conditions also affect the properties of the liquid and solid byproducts. There are processes to recycle these byproducts into building and paving materials; however, metals and other inorganic compounds are retained in these byproducts and can leach out over time due to water and weathering.

Table 5. Comparison of Thermochemical Conversion Technologies.[8]

Parameter	Pyrolysis	Gasification	Combustion	Plasma treatment
Temperature [°C]	250-900	500-1800	800-1450	1200-2000
Pressure [bar]	1	1-45	1	1
Atmosphere	Inert/nitrogen	Gasification agent: O_2, H_2O	Air	Gasification agent: O_2, H_2O Plasma gas: O_2, N_2, Ar
Stoichiometric ratio of oxygen	0	< 1	> 1	< 1
Main products from the process:				
Gas phase	H_2, CO, H_2O, N_2*, hydrocarbons	H_2, CO, CO_2, CH_4, H_2O,N_2*	CO_2, H_2O, O_2, N_2, NOx, SOx, HCl, VOCs	H_2, CO, CO_2, CH_4, H_2O, N_2*
Solid phase	Ash, coke (biochar)	Slag, ash	Ash, slag	Glassy slag, ash
Liquid phase	Pyrolysis oil and water			

*Combustion of these gas mixtures (syngas) following gasification, pyrolysis, and plasma gasification can create NOx and SOx; however, unlike direct combustion, there is an opportunity to remove products from the gas prior to combustion.

Such materials have to meet strict standards for leachability in California. Some high-temperature processes vitrify the ash to a glassy slag which has improved leachability properties.

2.3 Waste-to-Energy in California

2.3.1 Existing facilities

In 2008, 20% of California's renewable power came from biomass sources. While 60% came from combustion of woody materials, nearly 40% of that power was generated from landfill gas, municipal waste combustion, and anaerobic digestion (primarily from wastewater treatment and farm animal waste, with only one facility processing MSW) (Table 6). Although the State has three MSW incineration facilities, now almost thirty years old, only one is eligible for renewable electricity credits.[10]

Table 6. Waste-to-Energy in California in 2008.[10]

Technology/Fuel Source	Number of Facilities	Gross Capacity (MW)
Combustion of MSW	3	70
Landfill gas-to-energy	90	309
Wastewater treatment	20	64
Animal and food waste digester	22	5.7
Totals	**105**	**414.7**

2.3.2 Issues in Implementation

Waste-to-energy systems in California face three main inter-related barriers: technology restrictions in State statute, permitting, and finance. In an effort to enforce laudable environmental goals, the state has put in place specific and restrictive limits on siting, emissions, and eligibility for economic incentives such as diversion credits and renewable power status. Intersection of these restrictions has created extremely high barriers to the permitting process resulting in protracted or delayed project approval and extremely high costs, resulting in lost waste-to-energy opportunities and loss of investment dollars. This has affected implementation of almost every type of conversion process.

Pyrolysis and Gasification: While several biomass gasifiers utilizing wood or agricultural waste have been piloted in California, the current policy landscape for MSW gasification presents significant barriers to developers. Power produced through gasification of MSW is eligible for renewable status, while that produced by incineration is not.[11] However, the strict definition for delineating gasification from incineration has caused confusion and controversy. The rule states that the technology must accomplish conversion “without using air or oxygen except ambient air to maintain temperature control”. While pyrolysis can meet this definition easily, it is unclear if a combined pyrolysis-gasification system would.

Anaerobic Digestion: About 20% of MSW is considered suitable for anaerobic digestion. Several waste management districts including East Bay Municipal Utility District, Humboldt County, and Central Marin have embraced the technology. Efforts to implement anaerobic digestion on farms have been problematic due to a confluence of issues surrounding cost and emissions control. After a series of programs to incentivize on-farm digesters, farmers were faced with increasingly strict NOx emissions standards. The cost of improved systems has negatively affected implementation of the systems over several decades. No incentive

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[10] California Energy Commission (2010). "2009 Progress to Plan - Bioenergy Action Plan for California." Staff Report to the Bioenergy Interagency Working Group: 1-57.

[11] One of the currently operating “grandfathered” MSW incineration plants is considered RPS eligible but any new plants would not be eligible.

program for anaerobic digestion of municipal waste has been implemented. CalRecycle is now working to help provide environmental impact assessment reports and streamline the permitting process for new anaerobic digestion units to reduce costs and time in the permitting.[6]

Landfill Gas to Energy: Although landfill gas to electricity is inefficient relative to other waste-to-energy scenarios, capturing energy from existing landfill gas activities has positive environmental and economic benefits. The California Energy Commission states that "Regulating air quality pollutants by annual emissions (tons pollutant/yr) rather than by unit emissions (tons pollutant/kWh) can lead to missed opportunities and prohibit large facility development for biopower. For example, the Lopez Canyon Landfill in Los Angeles had 25 MW of available landfill gas resource; however, that facility could only obtain an air permit for 6 MW. The remaining gas must be flared."[6] Because of severe penalties on possible vinyl chloride contamination from California landfill gas, no utility will accept landfill gas from within the State. Ironically, the restriction does not hold for out-of-state landfill gas.

Acid Hydrolysis: Bluefire Ethanol (Irvine, CA) received State funding to develop a pilot facility in southern California to develop its concentrated acid hydrolysis technology on local municipal waste. The demonstration plant was in operation from 1995 to 2000. The company planned to build an 18 million gallon commercial-scale refinery in Mecca, CA and in 2007 received $40M in funding from the US Department of Energy[12] toward development of a commercial plant. Two years into the permitting process, the company decided to move out of the State stating that "Navigating the development and licensing process in California in a time effective manner coupled with the challenging business climate in the State convinced BlueFire to petition the DOE for a site change to Mississippi."[13]

3. Environmental Impacts

3.1 Assessing Impact of Waste-to-Energy Systems

All waste handling systems have emissions and environmental impact (Table 7). The challenge, both scientifically and with regards to policy incentives is to minimize this impact at reasonable social and economic cost.

The degradation of biomass by natural or industrial processes results in gaseous emissions which can include carbon dioxide, carbon monoxide, methane, nitrogen oxides and sulfur oxides, depending on the reaction conditions. The inorganic components in natural biomass include sodium, magnesium, potassium, chloride and trace metals such as iron and copper. Municipal waste also contains additional metals like aluminum, arsenic, lead, cadmium, and mercury which can reside in processed biomass such as paper, cardboard, textiles that contain dyes, paints, binding agents, etc., or unsorted/unrecovered contamination from

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[12] To date the company has received $88M from DOE.

[13] Biofuels Magazine October 2009 "Bluefire moves DOE-backed cellulosic project from California to Mississippi.

non-biomass components like detergents, household chemicals, plastics, glass, incandescent light bulbs, and batteries. These inorganics are retained in solid residues like compost, sludge, ash, filter cake, etc.

Table 7. Impact Comparison by Technology*[14]

	Landfill w/ energy recovery	Compost	Anaerobic Digestion	Hydrolysis	Incineration	Pyrolysis	Gasification
Energy Recovery	0.5 MJ*	▓	0.5-1.0 MJ (up to 2MJ with CHP)	25-80 gge	2 MJ (up to 6 MJ with CHP)	0.7-1 MJ	2 MJ
Fuel Production	Biogas	▓	Biogas	Ethanol/AH** Biogas	▓	Pyoil Syngas	Syngas/AH Chemicals
Nutrient Recovery/ Byproducts	▓	2-4 kg N 1-2 kg P 1-2 kg K	4.0-4.5 kg N 0.5-1 kg P 2.5-3 kg K	0.5-1 kg P 2.5-3 kg K	Metals (0.05)	Char (0.2-0.4)	Glass, Slag, Metals
Residuals to Landfill		0.02-0.1	0.02-0.1	0.02-0.1	Fly/Bottom Ash (0.12-0.25)	Char (0.02-0.3)	Ash, Slag (0.02-0.3)
Water Impact	Leachate	▒	Reclaimed Wastewater	Reclaimed Wastewater	Leachate from ash disposal		Leachate from slag disposal
Cost	Low	Low-Medium	Medium-High	High	Medium-Very HIgh	High	High-Very High
Scale	Small-Large	Small	Small-Medium	Medium	Medium-High	Small-Medium	High-Very HIgh

*all values are per Mg waste. The energy content of waste can vary from 10-20 MJ/Mg. Energy recovery refers to energy in excess of the process – energy that can be put to other uses.

**AH = advanced hydrocarbons produced from chemical catalysis or biological transformation

Positive Benefit	Benefit Unclear or Problematic	Poor Benefit/ Not Suitable
░	▒	▓

3.2 Life-cycle Analysis and Greenhouse Gas Emissions of Waste-to-Energy Systems

A survey of nearly 200 papers regarding LCA of waste conversion and waste management systems indicates that results to favor nearly any scenario can be found. Even simple questions such as whether composting is better than landfill or incineration lead to ambiguous conclusions. The situation is even worse when newer technologies are examined in detail.

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[14] Eunomia Research & Consulting, D. Hogg, et al. (2002). "Economic analysis of options for managing biodegradable municipal waste. ." Final Report to the European Commission: 1-202.

The combination of gross generalization across equipment configurations and operating parameters with variation in methodologies regarding systems boundary definition and impact allocation and offsets makes comparisons of different LCA outcomes nearly impossible.[15]

Table 8. Comparison of Implementation of Similar Technologies in the UK and Germany.[16]

Treatment method	**UK**			**Germany**		
	GHGS [kgCO_2 eq/t]	kg C in 1 t MSW	Carbon footprint [kgCO_2 eq]	GHGs [kgCO_2 eq/t]	kg C in 1 t MSW	Carbon footprint [kgCO_2 eq]
Waste-to-Energy	132*	86.4	11.4	321	311	99.8
Landfill	415.1	656.3	272.5	32.6	76	2.5
MBT	7.6	4.3	0	7.6	125	1.0
Anaerobic digestion	4.1	0.1	0	4.1	N.A.	N.A.
In-vessel composting	3.4	0	0	3.4	153	0.5
In-windrow composting	5.8	88.7	0.5	5.8	0	0
Sum Carbon Footprint**	175.3			33.5		

*N_2O not included **Includes data from recycling (not shown)

Uncertainty in the LCA of waste systems is introduced throughout the analysis. Differences in stakeholder behavior from product preference, product use and re-use, seasonal habits, and waste sorting can affect the composition of the waste stream regionally and temporally. This effect is compounded by variation in equipment configuration and operating parameters (affecting conversion efficiency). For example, comparison of similar technologies in the UK and Germany shows the effect of waste composition and management scenario (Table 8).

A smaller footprint for landfill in Germany (line 2) does not indicate that there is something magical about German landfill technology. The effect on landfill greenhouses gases is directly tied to the composition of the residual waste. Because the starting composition is different and a larger portion of waste is diverted to composting and energy production in Germany, the footprint of the residual material that is landfilled is smaller. Also notice that the greenhouse gas production of UK Waste to Energy is not really three times less that of Germany because the impact of nitrous oxide is not included in the analysis.

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[15] Gentil, E. C., A. Damgaard, et al. (2010). "Models for waste life cycle assessment: Review of technical assumptions." Waste Management 30(12): 2636-2648.

[16] Muhle, S., I. Balsam, et al. (2010). "Comparison of carbon emissions associated with municipal solid waste management in Germany and the UK." "Resources, Conservation & Recycling" 54(11): 793-801.

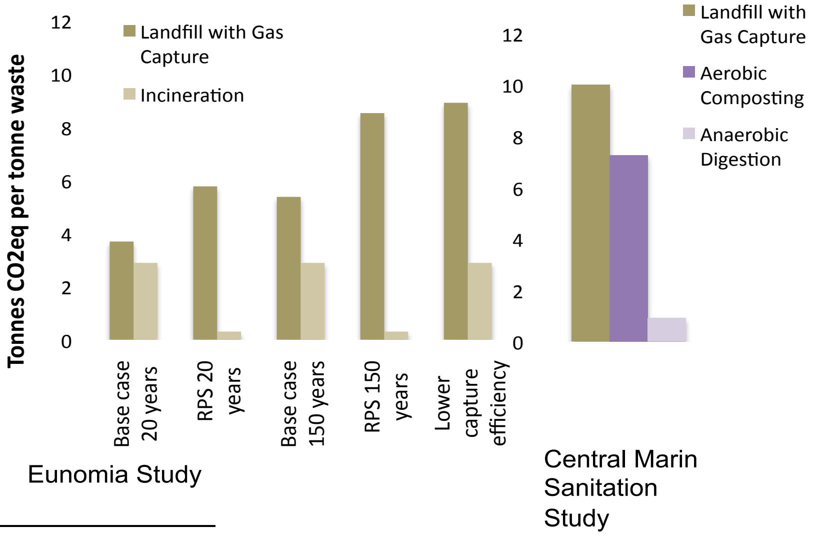
The literature in waste-to-energy conversion is further complicated by a lack of verified independent data and a plethora of reports by consulting firms that are paid by companies in the industry. Very few studies examine a wide slate of technologies which would allow application of consistent assumptions. Those that do often pull data from a variety of disparate, ultimately incomparable sources and homogenize them in the analysis such that it is almost impossible to tell if the results are even self-consistent.[17]

3.3 Air Emissions

Conversion efficiency and waste composition have large impacts on generation of criteria pollutants such as soot, dioxins, and volatile organic carbon (VOCs) in thermochemical systems and NOx emissions in biological conversion platforms. The capture and use of heat generated during conversion is also variable and can alone affect whether a waste-to-energy scenario is better or worse than landfill with gas recovery.[18]

For example, Figure 4 illustrates two different analyses[19] comparing MSW incineration to landfill with energy recovery. The graph clearly illustrates the effect of different parameters including length of time analyzed (20 vs. 150 years), waste composition (all waste in the base case vs. sorted waste in the RPS case), and efficiency of energy recovery (75% in the base case vs. 20% in the lower efficiency case). A separate study on composting by the Central Marin Sanitation Agency has yet a different value for landfill with gas capture.

Figure 4. Illustrating the effect of waste composition and analysis parameters on life-cycle carbon emissions from incineration of waste (mass burn) or landfill with energy recovery (landfill gas to electricity), composting and anaerobic digestion.[17]



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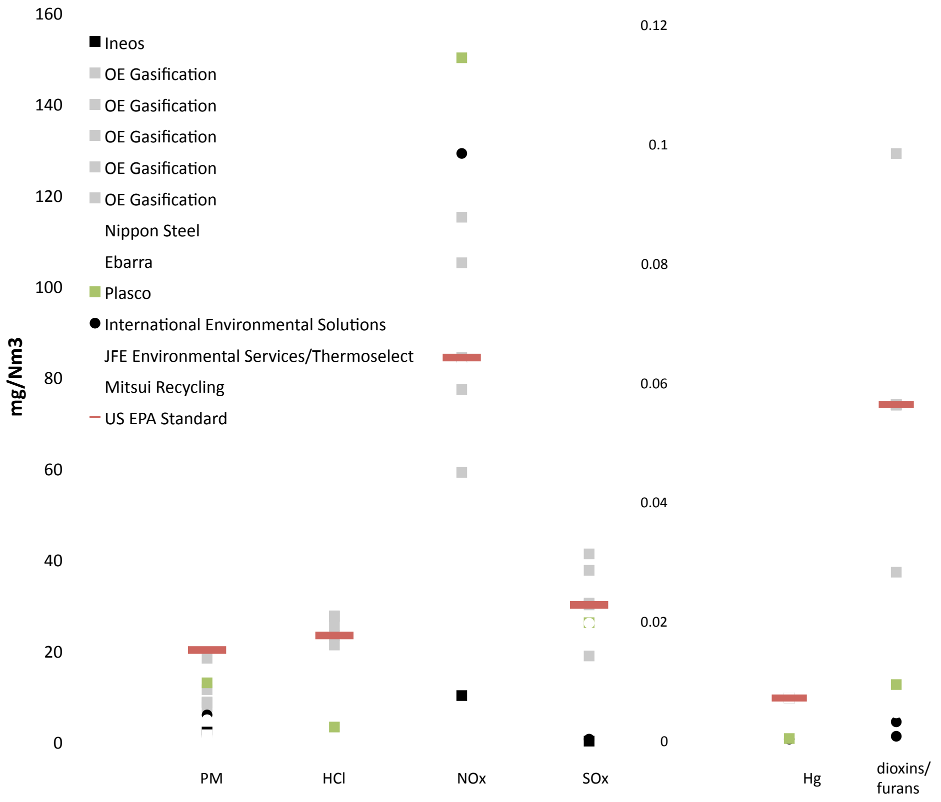
[17] Khoo, H. H. (2009) "Life cycle impact assessment of various waste conversion technologies." Waste Management 29(6): 1892-1900.

[18] Morris, J. (2010). "Bury or Burn North America MSW? LCAs Provide Answers for Climate Impacts & Carbon Neutral Power Potential." Environmental Science & Technology 44(20): 7944-7949.

[19] Ballinger, A.Eunomia Research & Consulting (2011) "Climate Change Impacts of Residual Waste Treatment." Report for UKWIN. Thorneloe, S. and K. Weitz (2004). "Sustainability and Waste Management." Solid Waste Association of America http://www.swana-wi.org/.

Due to limited landfill space and landfill policies, thermal technologies including incineration and gasification have been employed in the EU, Japan and Korea over the last decade. There are over 100 gasification plants operating in these countries, most installed in the last decade. A recent survey of air emissions from various functioning gasifiers in the US, Japan, and Korea, was recently conducted at UC Riverside. The data indicate that there are systems that can meet or exceed California standards, except possibly in areas of extreme non-attainment (Figure 5);[20] however, not all systems met the standards. It should be noted that Plasco Energy, Ottawa Canada has a project under development in Salinas and is a finalist for a possible project in Santa Barbara. The emissions data for the Plasco demonstration facility in Canada were the lowest in the study, well under the EPA standard for all emissions except NOx.

Figure 5. Emissions from gasification systems (top) and pyrolysis/gasification systems (bottom) in the North America (black), Japan (white), Korea (gray).[18] US EPA standard levels (red). All data is from 2005-2008*.



*It is important to not feedstocks for these facilities vary from mixed and post-recycled MSW to MSW incineration ash.

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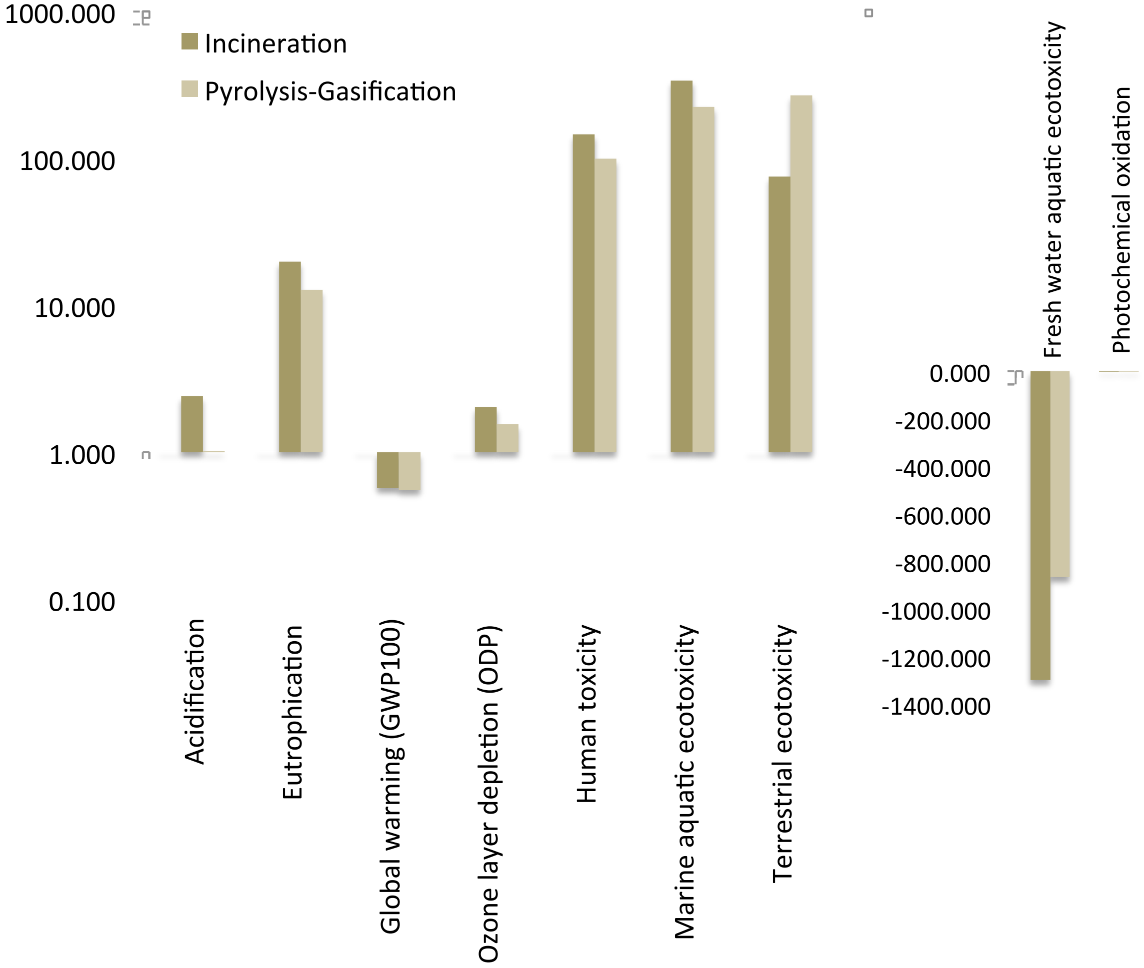
[20] UC Riverside (2009). "Evaluation of emissions from thermal conversion technologies processing municipal solid waste and biomass." Final Report for the Bioenergy Producer's Association: 1-42.

The solid and liquid by-products (stillage, sludge, ash, slag and landfill leachate) can have effects on aquatic and terrestrial ecosystems. Nitrogen and other nutrients cause eutrophication which increases biological oxygen demand, metal salts can have direct toxic effects and cause salinification and acidification, and metal oxides can cause alkalinization (Figure 6).

Figure 6. Toxicity effects of incineration and gasification relative to landfill.[21]



3.4 Impacts on Recycling and Shift to Renewable Materials

It is possible that implementing waste-to-energy systems will negatively impact efforts to reduce waste by creating an additional viable market for waste products. If subsidized and unchecked, there is concern that this new market could “pull” materials that would otherwise have been recycled. This is considered especially problematic if both diversion

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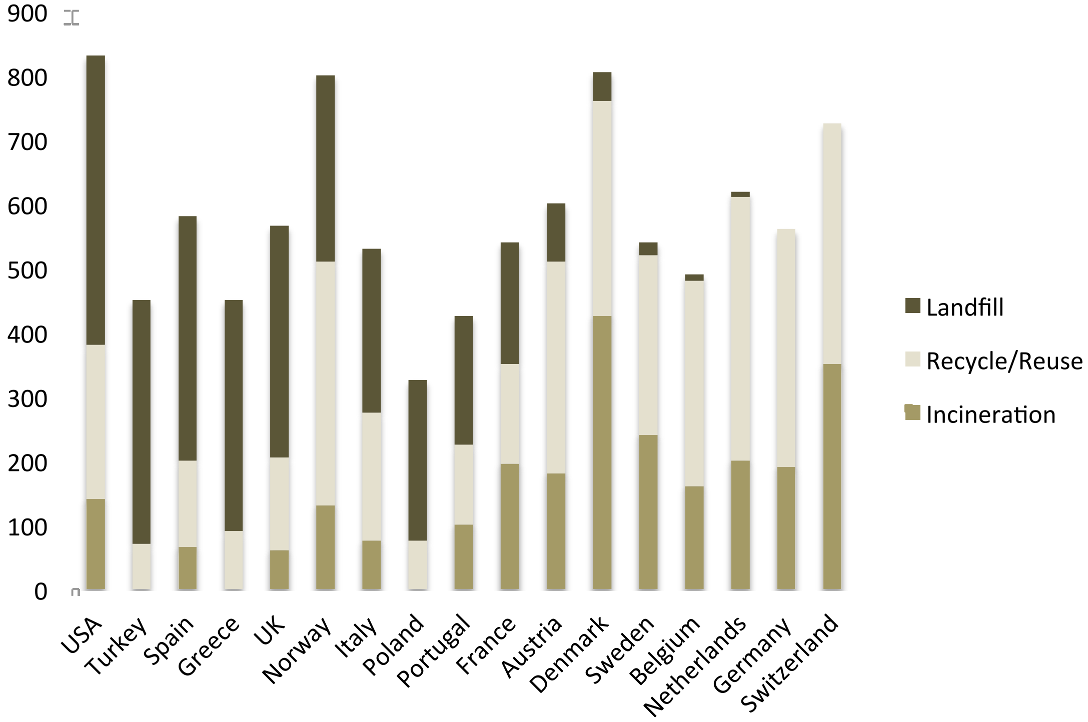
[21] Zaman, A. (2010). "Comparative study of municipal waste solid waste treatment technologies using life cycle assessment method." International Journal of Science and Technology 7: 225-234.

credits and renewable electricity credits are granted to a waste-to-energy facility. Even if only post-recycled material is used, it is possible that the incentive to reduce residuals by using new manufacturing materials or processes will be negated by a need to continually supply the waste-to-energy facility, which represents a sizable economic investment. In other words there is concern that an irrevocable "need to feed the beast" will develop and hamper progress toward maximum waste reduction. It is unlikely, however, that these types of market effects on recyclable or renewable materials will be realized in the near-term. Waste-to-energy facilities built in the next ten years will sunset within a few decades, when deep penetration of such alternatives are likely occur. So far this effect has not been observed in the EU, where zero-landfill policies have driven both waste-to-energy programs and high recycling rates (Figure 7). Despite implementation of waste-to-energy programs, Germany expects to increase recycling rates from 62% in 2006 to 72% in 2020.

Figure 7. Waste disposition in the U.S. and E.U. in 2007. Many countries with high rates of incineration (waste-to-energy) also have high recycle/reuse rates (Eurostat).



Future negative effects on recycling and material shift can be avoided by use of modular systems which can be up- or down-scaled to fit residual waste production rate. Many companies have already moved in this direction, recognizing the need to apply the technologies to municipalities with a wide range of annual waste. Alternatively, in extreme cases, other forms of renewable biomass such as agricultural or forest residues or purpose-grown woody or herbaceous energy crops can be substituted in to fill out the expected lifetime of the facility.

4. Socio-economic Considerations

4.1 Stakeholder Views

The main stakeholder groups associated with municipal waste decisions are the residents of the community, the waste processing industries, governing bodies, policy makers, and environmental non-governmental organizations (NGOs). When landfill is limited, waste-to-energy becomes increasingly attractive. A recent survey of stakeholders in Boston, a landfill capacity stressed area, revealed some important differences between the views of residents and local governmental agencies (Table 9).[22] Residents were far more concerned about health effects than costs.

Table 9. Ranking of Factors by Stakeholders in the Boston Area.[22]

Group	Health Damage	GHGs	Cost	Landfill Capacity
Residents	1	2	4	3
Local Government	2	4	3	1
NGOs	2	4	3	1

When studying questions around use of MSW incinerators, the National Research Council found that stakeholders have trouble understanding estimates of exposure and health risk when uncertainty and variability are high. This is certainly the case for advanced thermal conversion methods as portrayed by certain activist groups. Although there is no clear indication in the scientific literature that pyrolysis and gasification are the same as or worse than new incineration methods, NGOs that are opposed to the technology purposefully blur the lines. Reports with names like “An Industry Blowing Smoke” and “Black-bag Energy” boldly state that gasification is “incineration in disguise”[23] and conjure up images of a turn-of-the century soot spewing industrial monster. Unfortunately, in such a climate, energy companies all too often try to oversell the “green-ness” of their product making exaggerated claims of zero emissions and dressing up facilities as parks.[24] The resulting polarized environment only exacerbates the very difficult task of building a solid science-based consensus using the evolving and variable tool set of LCA. In this context in the US, the general acceptance of biological conversion systems is higher than thermochemical systems

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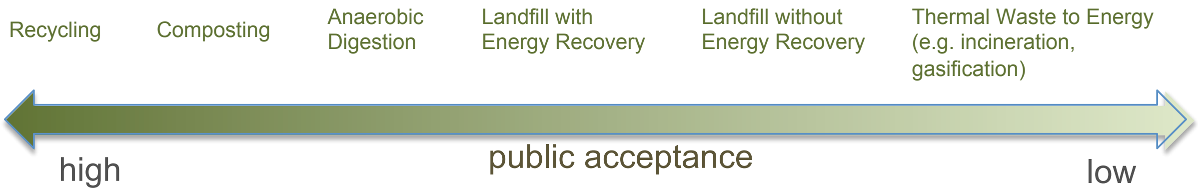
[22] Contreras, F., K. Hanaki, et al. (2008). "Application of analytical hierarchy process to analyze stakeholders preferences for municipal solid waste management plans, Boston, USA." Resources, Conservation & Recycling 52: 979-991.. Ranking based on calculated weight.

[23] Flynn, M. J. and R. Bingham (2007). "Black bag energy: Thermal treatment of waste using autoclaving and pyrolysis." Waste Management World November-December: 58-61, Ciplet, D., G. A. f. I. Alternatives, et al. (2009). "An Industry Blowing Smoke: 10 Reasons Why Gasification, Pyrolysis, & Plasma Incineration are Not "Green Solutions"." June 9: 1-40.; Global Alliance for Incinerator Alternatives, G. A. I. A. and G. f. H. E. Justice (2008). "Burning Issues in Waste Disposal: Incinerators in Disguise." October: 1-48.

[24] The Teeside gasification plant in the UK will be designed as a park with recreational viewing rooms and a volcano-like façade. http://inhabitat.com/new-biomass-plant-for-the-uk-looks-like-a-giant-green-volcano/

(Figure 8), even though the emissions from thermal systems have been reduced over 90% in the last decade.

Figure 8. Public acceptance of waste-to-energy technologies.



The situation is not the same in the EU or in some communities in the US that are extremely limited in landfill capacity. When landfill becomes a last option, the choice is often between direct energy recovery in the region where the waste is generated, resulting in local emissions risk balanced by local energy benefits, being weighed against export of the waste or a waste-derived fuel and associated risks and benefits.

4.2 Costs

Capital costs for waste-to-energy systems remain high. The capital costs of the various technologies can be ranked in comparison to coal (Table 10.)[25] Recently small-scale gasifiers in China and India have been implemented at lower cost, although these systems are not required to meet environmental standards equal to those in the US.

Table 10. Capital costs relative to coal electricity.[25]

Coal	Incineration	Pelletization/ Co-firing	Anaerobic Digestion	Pyrolysis to Electricty	Gasification to Electricity
1	1.2	0.62	2.2	1.6	2.5

Proposals of a several different conversion systems to both the City and County of Santa Barbara in 2008 indicate a wide range of projected costs as reflected in the tipping fee quotes made by various companies (Table 11).[26] While anaerobic digestion units could be competitive at these prices, thermal methods would have difficulty. For comparison, regular tipping fees at the County's Tajiguas landfill are $67/ton for regular waste and $55/ton for construction and demolition waste. California's mean landfill tipping fee is $40/ton.[27]

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[25] From Bloomberg New Energy Finance data. Bioenergy Insight Call 23 September 2010.

[26] Alternative Resources Inc. and Clements Environmental Corporation (2008). "Evaluation of municipal solid waste conversion technologies." Report to the City and County of Santa Barbara, California April: 1-108.. Prices may or may not include an anticipated diversion and renewable energy credits.

[27] US EPA 2008

Table 11. Tipping fees quoted to the City and County of Santa Barbara 2008.[26, 27]

Company	Technology	Tipping Fee ($/ton)	Quoted Diversion Rate
California Renewable Technology Inc.	Anaerobic Digestion	$50-$60	76%
Ecocorp	Anaerobic Digestion	$40	69%
AdaptiveNRG	Plasma Gasification	$50	95%
International Environmental Solutions	Pyrolysis-Gasification	$56	85-95%
Interstate Waste Technologies	Gasification	$71	100%
Plasco Energy Group	Plasma Gasification	$65-90	99%
Primenergy	Gasification	$55	78%
Tajiguas Partners	Gasification	$56-100	95%
World Waste Technologies	Gasification	$100	60%
Herhof California	Biological Drying	$100	70%
California Average	Landfill	$40	n/a

4.3 Policy Implications

4.3.1 Interagency Cooperation

In general, California has taken a critical yet optimistic view of energy recovery from municipal waste. In the past, efforts to implement policy incentives for bioenergy have fallen victim to some discord at the agency level and the interface between state and local government. Establishment of the Bioenergy Interagency Working Group, including representation of the California Air Resources Board, California Energy Commission, California Environmental Protection Agency, California Department of Food and Agriculture, California Department of Forestry and Fire Protection, California Department of General Services, California Natural Resources Agency, California Public Utilities Commission, California Department of Resources Recycling and Recovery, California Water Resources Control Board and California Biomass Collaborative, has helped to harmonize efforts and pool knowledge. This group has looked extensively at bioenergy-related science, technology, policy, and economics including issues surrounding organic materials in municipal waste. The recent 2011 Bioenergy Action Plan reflects this, addressing some of the key challenges in landfill gas recovery and implementation of anaerobic digestors in wastewater treatment facilities and on farms.

4.3.2 Should Waste-to-Energy be Eligible for Renewable Energy Credits *and* Diversion Credits?

According the International Panel on Climate Change (IPCC), biogenic carbon – carbon that is part of a natural cycle of biological carbon fixation into biomass that would normally be released through natural decay – is considered carbon neutral. All the organic carbon in municipal waste, except plastics and polymers produced from fossil sources, is biogenic and thus considered carbon neutral. Technically, such material falls perfectly within the definition for renewable energy credit in California. Since waste-to-energy is, by definition diverting some portion of material from landfill, it technically is eligible for diversion credit as well.[28]

Some have questioned whether this is "double-counting" or providing an undue incentive to route waste to energy, by-passing other diversion opportunities such as recycling and composting. This argument is a bit of red-herring. Incentivizing diversion from landfill should not be conflated with incentivizing downstream markets. Just as composted nutrients and recycled materials have special markets, the electricity generated from diverted organic material fills a specialized niche. It must compete with other renewable electricity within the portfolio as well as its fossil counterpart and thus, may be not be advantaged over other diversion products. If a particular diversion hierarchy is desired, that can be accomplished through tiered incentives or mandated diversion allocations; however, a full system integrated model may be needed to avoid unwanted indirect effects.

4.4 Possible Synergies

Countries which have successfully implemented biomass energy technologies, including waste-to-energy have taken advantage of synergistic energy needs and material flow. Co-generation of electricity and biofuels; production of fiber, heat and electricity; waste recycling, heat and electricity are all possible and have been implemented at commercial scale. Capture of low-grade heat for industrial use will lower state emissions. Capture of nutrients and metals that would otherwise go to landfill will decrease use of virgin and fossil materials and improve water quality. The current policy landscape surrounding waste in California seems to disincentivize such integration. Co-location of waste facilities will reduce pollution and costs by minimizing handling and transport of various waste streams. Options for synergy among bioenergy production technologies and with other industries are discussed in the 2011 Bioenergy Action Plan.[1]

5. Conclusions

Recovering energy from post-recycled organic materials can provide environmental benefits and need not impact other waste management goals. Carefully constructed policies can encourage waste reduction, recycling, landfill reduction, and energy recovery. Each waste system is different and may require different optimization of material flow and use of technology. Thermal conversion systems including pyrolysis and gasification can meet environmental standards when implemented properly but may not be suitable for all waste components or systems.

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[28] Any residual sludge, slag or ash that must be landfilled a the end of the conversion process should be counted against the diversion credit.

6. Appendix

6.1 Waste-to-energy conversion requirements to meet the California Renewable Portfolio Standard[29]

California Public Resources Code (PRC), 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 percent of all solid waste through source reduction, recycling, and composting.

Renewables Portfolio Standard Eligibility, (Commission Guidebook, January, 2011) Pg.28:

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 (gasification3 conversion) a non-combustion 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, 2) it is located in-state or satisfies the out-o fstate requirements, and 3) the facility and conversion technology meet all of the following applicable criteria in accordance with Public Resources Code Section 25741, Subdivision (b)(3) [which are identical to provisions a-g above].

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[29] PRC §25741 (3)

6.2 Life-cycle analysis: A cautionary tale

LCA was originally designed to systematically track material and energy flows for a given process using a tightly defined equipment configuration. For example, understanding the annual flow of fossil fuels, chemicals, wood pulp, water, etc. that are used to manufacture paper, using in a particular technology. Within the system boundary of the plant, the life-cycle inventory could be used to get a general idea of energy and material use and thus calculate operating costs. Later the technique was used to assess waste products such as acidified water or sulfur dioxide gas and thus calculate a rudimentary environmental impact. As LCA systems have been refined, material, energy, and environmental impacts have been generalized for a "typical" plant (rather than a specific plant) using averaged data from several working plants. Naturally, the more variation there is in process variables and configurations, the more uncertainty is introduced into the average output of the LCA. Recently, LCA models have been expanded in several very important ways that increase uncertainty in the analysis and thus the ability to compare LCA studies.

First, the system boundaries have been expanded beyond the plant to include processes "upstream" and "downstream" of the activity. In the example of a paper plant, this includes accounting for manufacturing of the plant equipment, planting, harvesting and storage of the woody material use for pulp, manufacturing and operation of the silivicultural equipment, seedling production, etc. upstream of the plant and paper distribution and end-use on the downstream side. When products replace or offset other processes, they cause a change in the total LCA. For example, if the paper mill burns it's residual lignin to create electricity and export that to the grid, they can apply an offset for the fossil energy that would have been used to generate that electricity. It is obvious that whereas the original system boundary of the plant was well-defined, these expanded system boundaries are not and different researchers choose to include different upstream and downstream processes and offset methods. The more products produced in the plant, the more convoluted these relationships can become.

Second, system boundaries have been expanded to include consequential or indirect effects of a process. For example, the LCA of a paper plant might now include the indirect effect of planting trees on what was once agricultural land, which will now force that agricultural activity, through market forces, to be shifted to Brazil resulting in loss of an acre of rainforest, a negative impact. Alternatively, better efficiency in the pulping process might cause an decrease in mill residues that were used to make particle board which now must be replaced with increased use of recycled plastic resins which has the positive effect of creating a market for recycled plastic.

Third, the system boundaries are being expanded in time. The annual environmental impact is insufficient, for example, to fully account for the buildup of greenhouse gases that occurs over time. This is particularly important in comparing single time-point processes like incineration to gradual processes such as decay in a landfill that may take 30 or 100 years. Finally, as systems become broadened, often more than one product is produced per input.

The method used to allocate material, energy, and environmental impacts to each product can vary. For example, if the paper plant produces fiberboard from the sawdust in addition to the paper, how do the impacts get allocated to each product, by mass, volume, energy content, economic value? All these methods are valid and used. One must take great care in comparing any two LCA impact studies to ensure that comparable methods and systems boundaries are used.

LCA, done properly with consistent methodology and assumptions can provide crucial information to help guide decision making and assess possible environmental risks. Caution should be applied to LCA that extends beyond the original intent of the tool.

6.3 Additional Resources

Science Applications International Corporation, Ratafia-Brown, J., L. Manfredo, et al. (2002). "Major environmental aspects of gasification-based power generation technologies: Final report." Report to the Gasification Technologies Program, US DOE NETL 270pp.

The Electric Power Research Institute (EPRI) (2011) “Waste-to-Energy Technologies: Opportunities for Expanding Renewable Generation & Reducing Carbon Emissions” 26pp.

Schwager, J. and K. Whiting (2003). "Progress toward commercialising waste gasification: A worldwide status report." Presentation to the Gasification Technologies Conference San Francisco (14 October): 26pp.

Circeo, L. J. (2009). "Plasma Arc Gasification of Solid Waste." February 17, 2009 AB 118 Workshop: 1-25.

Pavlas, M., M. Touš, et al. (2010). "Waste to energy – An evaluation of the environmental impact." Applied Thermal Engineering 30(16): 2326-2332.

Psomopoulos, C. S., A. Bourka, et al. (2009). "Waste-to-energy: A review of the status and benefits in USA." Waste Management 29(5): 1718-1724.

Helsen, L. and A. Bosmans (2010). "Waste-to-Energy through thermochemical processes: matching waste with process." 1st International Symposium on Enhanced Landfill Mining, Houthalen-Helchteren October 4-6: 41pp.

UK Associate Parliamentary Sustainable Research Group (2010). "Waste Management Infrastructure - Incentivising Community Buy-In." A report by the Associate Parliamentary Sustainable Research Group: 44pp.

Pytlar Jr., T. S. (2007). "Waste conversion technologies: Emergence of a new option or the same old story?" Presentation to the Federation of New York Solid Waste Association's Solid Waste & Recycling 9 May: 27pp.

Kaplan, P. O., S. R. Rajithan, et al. (2009). "Use of life-cycle analysis to support solid waste management planning for Delaware." Environmental Science & Technology 43(1264-1270): 1-7.

Lam, C. H. K., A. W. M. Ip, et al. (2010). "Use of Incineration MSW Ash: A Review." Sustainability 2(7): 1943-1968.

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Del Borghi, A., M. Gallo, et al. (2009) "A survey of life cycle approaches in waste management." Int J Life Cycle Assess 14(7): 597-610.

Williams, R. B., B. M. Jenkins, et al. (2003) "Solid waste conversion: A review and database of current and emerging technologies." Final Report to the California Integrated Waste Management Board IWM-C0172 129pp.

DEFRA (2004). "Review of Environmental and Health Effects of Waste Management." 420pp.

Yi, S., K. H. Kurisu, et al. (2011). "Life cycle impact assessment and interpretation of municipal solid waste management scenarios based on the midpoint and endpoint approaches." Int J Life Cycle Assess 16(7): 652-668.

Cleary, J. (2009). "Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature." Environ Int 35(8): 1256-1266.

Dvořák, R., T. Pařízek, et al. (2009). "Incineration and gasification technologies completed with up-to-date off-gas cleaning system for meeting environmental limits." Clean Tech Environ Policy 11(1): 95-105.

Becidan, M. l., L. Sørum, et al. (2010). "Impact of Municipal Solid Waste (MSW) Quality on the Behavior of Alkali Metals and Trace Elements during Combustion: A Thermodynamic Equilibrium Analysis." Energy and Fuel 24(6): 3446-3455.

Eriksson, O. and A. Baky (2010). "Identification and testing of potential key parameters in system analysis of municipal solid waste management." Resource Conserv Recyc 54(12): 1095-1099.

Pikon, K. and K. Gaska (2010). "Greenhouse Gas Emission Mitigation Relevant to Changes in Municipal Solid Waste Management System." J Air Waste Manage 60(7): 782-788.

Alternative Resources Inc. and Clements Environmental Corporation (2008). "Evaluation of municipal solid waste conversion technologies." Report to the City and County of Santa Barbara, California April: 1-108.

Jensen, J. W., C. Felby, et al. (2010). "Enzymatic processing of municipal solid waste." Waste Manage 30(12): 2497-2503.

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Byun, Y., W. Namkung, et al. (2010). "Demonstration of Thermal Plasma Gasification/Vitrification for Municipal Solid Waste Treatment." Environmental Science & Technology 44(17): 6680-6684.

Earles, J. M. and A. Halog (2011). "Consequential life cycle assessment: a review." Int J Life Cycle Assess 16(5): 445-453.

Consonni, S. and F. Vigano (2010). "A comparative analysis of two waste gasification technologies." Third International Symposium on Energy from Biomass and Waste Venice, Italy(November): 1-16.

6.4 Author Profile

Heather Youngs is an Analysis Fellow at the Energy Biosciences Institute at UC Berkeley and an adjunct professor of biochemistry at Michigan Technological University. Dr. Youngs received her Ph.D. in Biochemistry and Molecular Biology from Oregon Health and Sciences University and was a NIH postdoctoral fellow at the Carnegie Institute for Plant Bioloogy at Stanford University. Specializing in the structure and function of plant and fungal proteins, she has studied the enzymology of plant biomass synthesis and degradation for over fifteen years. At the EBI, Heather provides strategic assessments and detailed technical analysis of the entire bioenergy value chain including feedstock production, biomass depolymerization, and socio-economic and environmental impacts. In particular, she has published and lectured on production of lignocellulosic fuels from Miscanthus and Energycane, water footprints of biofuels, sustainable use of woody feedstocks for bioenergy, commercial development of biofuels and biogas, stakeholder views affecting feedstock choices, and technologies to enable continuous processing of lignocellulosic biofuels.

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