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WASTE COMPOSITION IN THE NORTHEAST U.S. – IMPLICATIONS FOR RESOURCE RECOVERY

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ABSTRACT

Waste composition studies can provide meaningful data for design and operation of resource recovery processes. However, relatively limited attention has been devoted to energy recovery predicted by waste composition analysis, despite increasingly detailed analysis of various subsets of the municipal solid waste stream. Further, global economic conditions and markets have dramatically altered since 2008, resulting in significant changes in corporate, institutional and consumer spending patterns. Associated with these shifts in spending, as well as with longer-term trends in packaging and advances in residential and commercial recycling, the quantity and makeup of discarded materials has changed. The authors present data resulting from recent waste composition studies, and discuss potential impacts on the design and operation of material recovery systems.

INTRODUCTION

Following a long-standing tradition in combustion practices, plant operators and engineers have sought to identify correlations between fuel composition and the fuel heating value. Perhaps the most widely referenced methods derive from the 19th century work of Dulong and based on properties of coal samples, and use empirical constants to calculate an expected higher heating value based on the fuel ultimate analysis. As with the widely practiced reliance on ultimate and proximate analyses in coal characterization, other studies examined components of the waste stream and reported characteristic composition with applied empirical calculations to estimate higher heating values. Channiwala and Parikh present a comparison of the various methods and associated shortfalls and expected deviation from values obtained using a bomb calorimeter.[1]

Such methods have been refined over the past 50 years, with increased attention to refinements in the empirical calculations during the 1990s and later based on biomass feedstock, resulting in variants of the empirical approach which alternatively use either the fuel proximate analysis or ultimate analysis, and some techniques have been abbreviated to consider only some constituents (such as C, H, O).[2] For the most part, studies which compare such empirical approaches to “actual” results rely upon relatively inexpensive laboratory tools, such as a bomb calorimeter, ASTM D 2015-85, to determine the “true” value. One potential shortfall of this technique is the small sample size employed (1 g), which may be suitable for homogeneous samples, but perhaps lack sufficient means to account for wide variations in fuel composition.

Extensive work done in the 1960s and 1970s was performed to examine techniques for relating the composition of municipal refuse and calculating heating values based on the composition of major constituents (e.g., paper, plastics, food waste, inerts, etc.).[3] This methodology is an international endeavor, as various authors present data and correlations to reflect the makeup of waste in their respective nations.[4] As noted above, the adiabatic bomb calorimeter is the tool of choice in most instances to establish the reference value, and statistical analyses typically are used to compare the calculated HHV with results of ASTM 2015-85 method,[5] and report variance based on the difference. Sample sizes as large as 10 t are reported to have been used.[6] [note that Chang et al. used 50 kg samples]

Some studies report fairly close correlation between heating values determined experimentally and those which utilize empirical formula, with variance measurements at slightly under 2%. Adjustments to the empirical formulae sometimes incorporate calculations to account for inorganic carbon and oxygen (bound as carbonate, for example) to improve precision. In some research, the composition of plastics (ultimate analysis) is reported for different polymers, which have varying C, H and O fractions which prove significant when employing empirical methods based on elemental composition.

What is lacking in most of the literature on the subject of waste composition and HHV is how well empirical formula compare with established protocols for commercially operating systems which measure HHV indirectly, such as the "Boiler-as-a-calorimeter" method[7] or the Specific Steam Correlation method.[8] The former, for the most part, ignores the fuel ultimate analysis but does take into account unburned carbon and fuel moisture; the latter relies only on scale data to approximate the mass feed rate, but not the composition, of MSW charged to the boilers.

The authors of this study discuss waste characterization data to analyze impacts of waste generating sector, seasonality, and time series trends in waste composition data. Two studies conducted in the northeastern U.S. are used as the basis for the analysis. The paper also examines monthly HHV data derived by the Specific Steam Correlation method to determine what, if any, associations are apparent between waste composition data and calculated HHV.

WASTE CHARACTERIZATION CASE STUDIES

Waste composition studies involve the representative sampling, sorting, weighing, and otherwise measuring individual constituents and other characteristics of wastes originating within the targeted waste shed. Such composition studies have been performed on wastesheds spanning individual cities and counties, scaled up to state-wide wastesheds. To date, state-wide waste characterization studies have been performed for over one-quarter of U.S. states, and county- or city-specific waste characterization studies have been conducted for hundreds of municipalities.

Procedures for waste composition analysis have been in existence for decades, with the most widely cited protocol being ASTM D 5231-92.[9] This protocol, as well as most of the variations that have been widely used, include procedures for (a) determining the number of samples needed to achieve reasonably low levels of relative error for the mean composition estimates; (b) selecting a representative distribution of incoming trucks that have collected wastes from within the targeted wasteshed; (c) obtaining a representative sample of waste material from within each tipped load; (d) sorting the samples into individual constituents and weighing the relative contribution of each constituent to the overall sample, and (e) calculating the mean, standard deviation and confidence intervals (usually at a 90 percent level of confidence) of the sample data.

There have been a number of recent waste characterization analyses performed in the Northeast and MidAtlantic regions. The City of Philadelphia is currently updating a city-wide residential waste characterization study that was last performed in 2000,[10] with final results due in mid-2010. In 2009, the Connecticut Department of Environmental Protection (CT DEP) sponsored a state-wide waste characterization study that was performed at five of the state's facilities permitted to receive the material – four of these facilities were waste-to-energy plants.[11] The Delaware Solid Waste Authority conducted a state-wide waste characterization study in 2006 that sampled at each of the state landfills and transfer stations.[12] Montgomery County, Maryland has been conducting waste characterization studies every five years since the mid 1990s.[13] New York City has conducted comprehensive waste characterization studies roughly every decade to assess their residential waste stream, with the most recent iteration completed in 2004 and 2005.

Selected findings from three of the waste composition projects mentioned above are provided to highlight findings and observations of interest. Figure 1 and 2 show the resulting aggregate waste composition by material group for the Montgomery County and Connecticut Statewide studies, respectively. Additionally, Figure 3 shows the composition of generated wastes according to the U.S. EPA's most recent national study.

FIGURE 1 MONTGOMERY COUNTY (MD) WASTE COMPOSITION, 2009

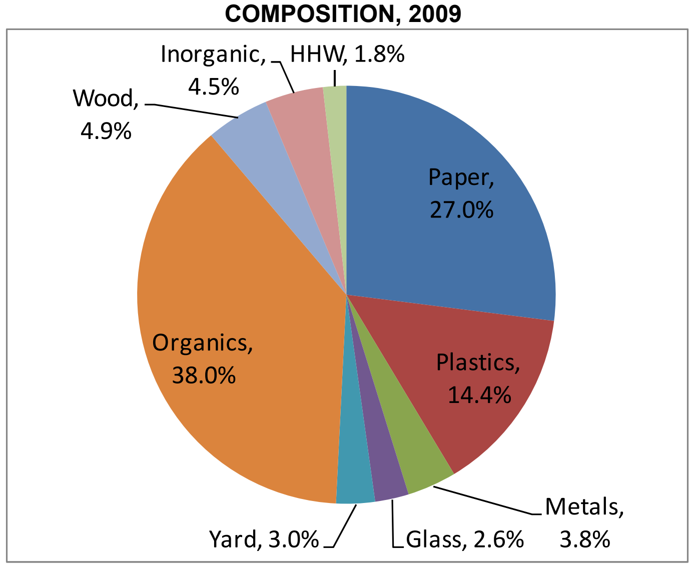


FIGURE 2 CONNECTICUT STATEWIDE WASTE COMPOSITION, 2009

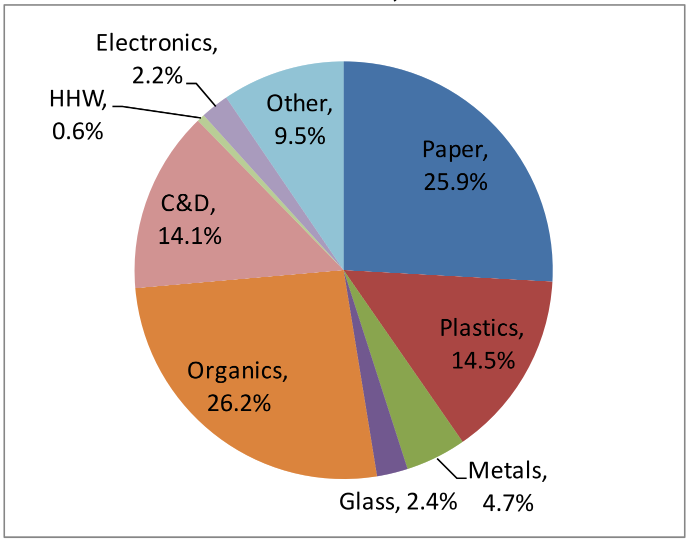
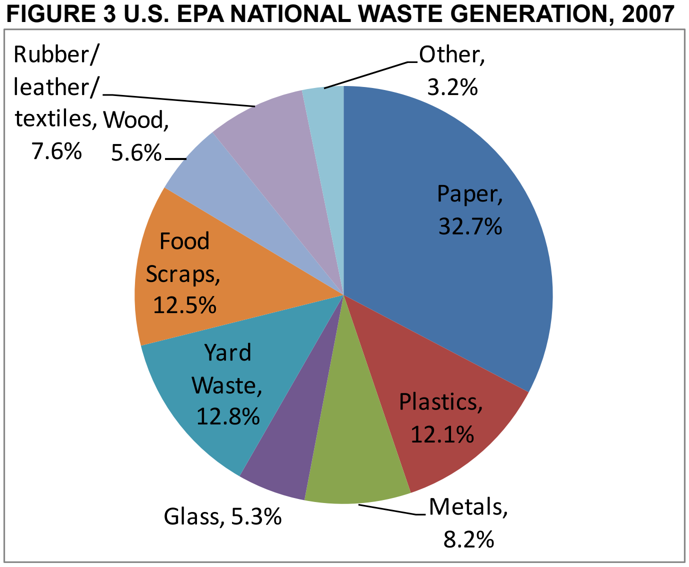


FIGURE 3 U.S. EPA NATIONAL WASTE GENERATION, 2007



An important observation from these three graphs is that every waste composition study defines the material categories and material groups independently. While this certainly allows waste composition studies to be customized to best inform each project sponsor, the inconsistency among studies increases the difficulty at comparing and applying their results to subsequent analysis of heating value.

Montgomery County, MD.

Any individual waste composition study provides a snapshot of the waste stream composition at the time of the study. Since the mid-1990s, Montgomery County, Maryland, has performed substantially identical studies over five to six year planning periods. This data is important to the County for purposes of planning and program evaluation as part of a comprehensive, integrated waste management system which includes a 1,700 tpd mass burn energy recovery combustor (owned by the Northeast Maryland Waste Disposal Authority for the sole benefit of Montgomery County), 360 tpd material recovery facility, composting, electronics recycling, and household hazardous waste recovery operated at the County's Transfer Station. In each waste characterization study, sampling and sorting events were conducted over two or four seasons at the County's central transfer station, with samples allocated across single family, multi-family, and non-residential generator sectors.

Because the field test and analytical methods for these studies has remained relatively constant, these data sets are informative about changes in the disposed waste stream over time. Table 1 shows selected material constituents and material groups for the most recent three studies.

TABLE 1 MONTGOMERY COUNTY WASTE COMPOSITION, SELECTED RESULTS 1998 THROUGH 2009

	Mean Composition by Year		
Material Group/Constituent	2009	2005	1998
Paper	**27.0%**	**40.3%**	**38.2%**
ONP	2.8%	4.3%	5.4%
OCC	2.8%	10.9%	7.2%
Mixed Recyclable Paper	11.5%	14.9%	16.2%
Plastic	**14.4%**	**13.1%**	**10.2%**
Plastic Bottles #1 & #2	1.9%	1.5%	1.2%
Organics (excl Wood & Yard Waste)	**38.0%**	**28.7%**	**27.4%**
Food Waste	19.6%	16.0%	15.3%
Metal	**3.8%**	**4.6%**	**5.7%**
Steel and aluminum cans	1.2%	1.1%	1.2%
Glass	**2.6%**	**2.4%**	**3.8%**
Glass Bottles & Jars	2.4%	2.1%	2.5%
Yard Waste	**3.0%**	**1.2%**	**2.4%**
C&D Debris (Incl Wood)	**9.4%**	**9.3%**	**11.4%**
HHW	**1.8%**	**0.3%**	**0.9%**

There appear to be consistent trends discernible in this data. For example, there has clearly been a decline in the percentage of paper in Montgomery County's disposed waste stream. Plastics have increased steadily, as have organic wastes. Likely contributors to these trends will be discussed below.

Connecticut Statewide

The most recently completed large scale waste composition study was performed by the Connecticut Department of Environmental Protection. The 2009 Connecticut Statewide Waste Characterization Study (Connecticut Study) spanned two seasonal sampling and sorting periods, with field data collected at four WTE plants and a municipal transfer station. A total of 258 samples of waste were obtained in the study, with each sample falling between 200 and 300 pounds. The waste stream was divided into 68 separate constituents, grouped into nine material groups.

The Connecticut Study (like many waste composition studies) separately analyzed wastes originating from the residential sector (including single family and multi-family dwellings) and the industrial/commercial/institutional (ICI) sector. Table 2 provides composition data for major material groups and selected constituents.

TABLE 2 CONNECTICUT STATEWIDE WASTE COMPOSITION BY GENERATOR SECTOR

		Aggregate	Residential	ICI
Paper		**25.9%**	**24.9%**	**27.2%**
	OCC	5.9%	2.6%	10.2%
	Office Paperr	1.9%	1.8%	2.2%
	Mixed Recyclable Paper	6.9%	7.9%	5.6%
Plastic		**14.5%**	**13.0%**	**16.2%**
	Plastic Bottles #1 & #2	1.3%	1.4%	1.3%
	Film Plastics	4.6%	4.9%	4.2%
Metal		**4.7%**	**4.8%**	**4.6%**
	Aluminum & Steel Cans	1.1%	1.2%	1.0%
Glass		**2.4%**	**2.6%**	**2.1%**
	Glass Bottles	1.8%	1.9%	1.6%
Organics		**26.2%**	**31.2%**	**19.8%**
	Food Waste	13.1%	13.2%	12.9%
	Yard Wastes	9.7%	13.5%	4.9%
C&D		**14.1%**	**10.7%**	**18.4%**
HHW		**0.6%**	**0.4%**	**0.7%**
Electronics		**2.2%**	**2.4%**	**2.0%**
Other Wastes		**9.5%**	**9.9%**	**9.0%**

As shown, the Connecticut study found only moderate variation between residential and ICI wastes. Yard waste was found in this study to be significantly higher in the residential stream, while the ICI stream contained higher fractions of paper, plastics, and construction and demolition (C&D) debris.

New York City Residential Waste Composition

New York City conducted a Preliminary Waste Composition Study on its residential waste stream in 2004 that included relatively extensive testing of sorted materials for contamination. Specifically, after each sample was sorted, subsamples of certain constituents were collected, sealed, and lab tested to determine (a) moisture content of the subsample, and (b) the fraction of cross-contamination (whether occurring at the generator source or during the collection process) of solid particles in the sample. Table 3 shows the resulting moisture content observed in the NYC data, compared against published moisture content.

TABLE 3 COMPARISON OF NYC RESIDENTIAL WASTE MOISTURE WITH PUBLISHED SOURCES

	Percent Moisture		
Material - NYC	**NYC PWCS**	**Meraz**	**Difference**
Aluminum Cans	17.0%	NA	17.0%
Aluminum Foil/Tins	26.9%	NA	26.9%
Clothing Textiles	14.0%	10.0%	4.0%
Compostable/Soiled/ Waxed OCC	42.7%	20.0%	22.7%
Expanded Polystyrene	27.0%	0.2%	26.8%
HDPE Colored Bottles	6.9%	0.2%	6.7%
HDPE Natural Bottles	7.3%	0.2%	7.1%
High Grade Paper	13.4%	0.0%	13.4%
Mixed Low Grade Paper	25.6%	10.2%	15.4%
Newspaper	28.6%	25.0%	3.6%
Non-Clothing Textiles	19.7%	25.0%	-5.3%
Other Nonrecyclable Paper	24.4%	23.0%	1.4%
Other Film	35.3%	0.0%	35.3%
Other Rigid Containers/Packaging	12.2%	15.0%	-2.8%
Paper Bags	29.4%	5.8%	23.6%
Paperbacks	8.0%	10.2%	-2.3%
PET bottles	11.8%	0.2%	11.6%
Phone books	7.1%	10.2%	-3.1%
Plain OCC/Kraft Paper	31.3%	5.2%	26.1%
Plastic Bags	34.9%	0.0%	34.9%
Polycoated Containers	22.2%	6.1%	16.1%
Rigid polystyrene	14.0%	0.2%	13.8%
Single Use Plates	34.2%	23.0%	11.2%
Single-Use Food Svc	17.9%	15.0%	2.9%
Tin Food Cans	10.1%	NA	10.1%

It is of particular interest that the moisture content observed in a relatively extensive moisture testing protocol during an actual waste composition study consistently exceeds the moisture content cited for use in HHV calculations in the Meraz paper. It is also worth noting that, in all likelihood, the actual total moisture in incoming loads of municipal solid waste is actually higher than what is captured in the field data. This is because of the practical obstacle associated with capturing loose moisture within a tipped load during the load sampling process. Extensive observation by author Culbertson suggests that both precipitation, as well as the liquid portion of solid wastes (for example, discarded beverages and food from commercial food preparation activities), flows immediately under the tipped load where it is absorbed in the dirt (if the waste composition study is being conducted on a landfill face) or dissipates on a concrete floor (if the waste composition study is being conducted in a processing facility with a pad). The standard grab sampling (or coning and quartering) suggested by waste composition protocol is not capable of capturing the contribution of such moisture.

Global Economic Downturn and Changes in Waste Composition

While it is common knowledge among solid waste management professionals that waste flow has been impacted by changes in global economic conditions as a result of the worldwide recession of 2008, the overall change in waste composition directly tied to economic conditions is not well understood, and continues to evolve. A few brief notes addressing recent developments are noted below:

1. Newspaper circulation and subscriptions for several hundred major U.S. daily publications declined by more than 10% from April to September 2009. In addition to the drop in circulation, advertising revenue for these publications dropped by about 28% this year, thus contributing to fewer overall pages and less newspaper in the waste stream.[14]

2. The American Forest & Paper Association (AF&PA) reported that U.S. paper and paperboard capacity declined 0.8% in 2008, and paper and paperboard capacity has contracted 7.3 percent since its peak level in 2000. Paper and paperboard capacity are projected to decline further in 2009 by 1.8%.[15]

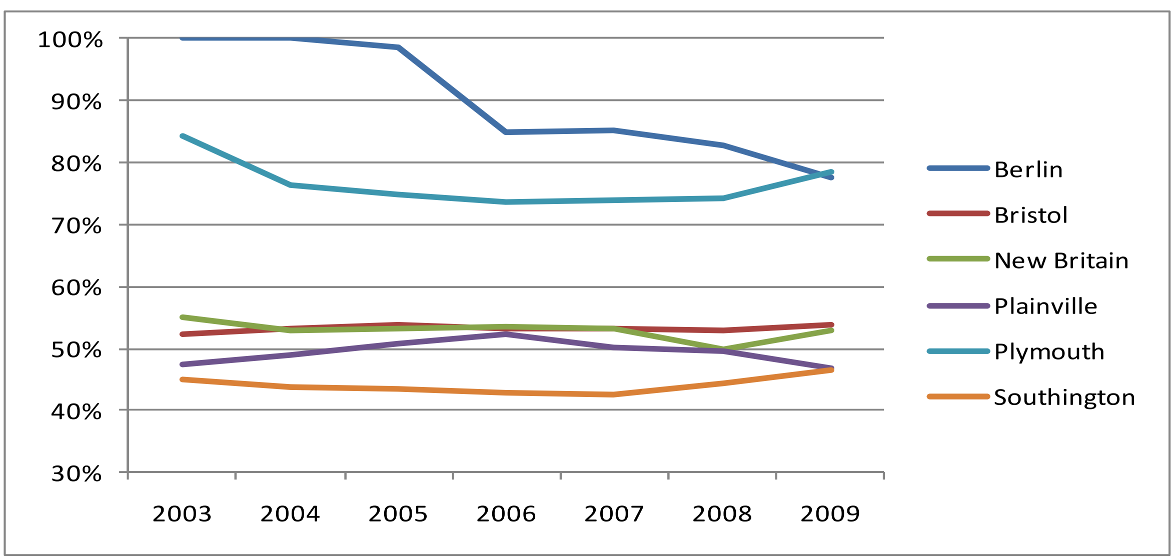
3. Corrugated box shipments for the first 10 months of 2009 dropped by about 9.6% compared to the same period in 2008.[16]

4. PET resin production, used to produce bottles and jars, dropped by 5.6% in 2008 compared to the previous year, and a trade association reported "2008 was a year like no other… for the PET packaging and recycling industry. The growth in the PET bottle markets that the industry had taken for granted for almost thirty years flattened and then reversed itself."[17] Similarly, HDPE bottles in the marketplace, primarily used for milk bottles, declined by 8.6%.[18]

Two important sources for reporting waste generation and recycling trends are the USEPA "Municipal Solid Waste in the United States"[19] and *Biocycle* "State of Garbage".[20,21] Since these reports are published biennially, it is too early to refer to these sources for data concerning the 2008 economic downturn. We can, however, examine data from the Montgomery County, MD study which included waste sorts conducted in Fall 2008 and Spring 2009 to discern whether trends are apparent, and if so, what are the implications for resource recovery.

Relative contributions of residential and commercial waste are considered for the Bristol Resource Recovery Facility; Figure 4 illustrates percentage of residential-to-total waste delivered to the Bristol Facility from each of six municipalities over a seven-year period. As shown, the residential/ICI mix varies significantly from several of the municipalities, likely from a combination of factors including local hauling dynamics as well as overall waste generation variability. Although not shown in the Figure, the overall residential/ ICI split ranges from 53% to 55% over the seven year time period.

FIGURE 4 – RELATIVE CHANGES IN CONTRIBUTION OF RESIDENTIAL WASTE TO TOTAL WASTE DELIVERIES FROM SIX BRRFOC COMMUNITIES



WASTE COMPOSITION AND HEATING VALUE

Previous Studies

Meraz et al. present an approach to calculating HHV based on the elemental composition of various fractions of the waste stream.[22] Of particular interest for this paper are studies which relate HHV and change in waste composition. Three particular sources are noted here.

1. Chang et al. reviewed historical waste generation and composition data for two MSW-fired plants in Taiwan, and noted that increased recycling and food waste diversion potentially account for measurable variations in waste HHV. The authors report that increased food waste diversion and higher proportion of plastics in the waste stream both contribute to observed increases in heating value.[23]

2. Magrinho and Semiao[24] considered paper and plastics recycling, as well as food waste recycling, with respect to variations in predicted LHV and HHV; while previous studies reported HHV as a critical parameter, the authors state LHV is a more critical metric as it better represents energy available for thermal conversion. As expected, reducing the relative concentration of inerts, such as glass, corresponds to a predicted increase in HHV, while the converse is true when increasing the plastics recycling rate. For HHV theoretical changes, increasing the recovery of food waste decreases the value, however when calculating LHV, the opposite trend is reported and LHV increases exponentially with increase food waste recycling. This is attributed to the effect of moisture in the fuel.

3. Marginal and second order effects of recycling on processing costs and HHV are reported by Montgomery County, MD.[25] A simple algorithm is employed to illustrate the impact of varying HHV on electric revenue, wherein HHV of the aggregate feedstock is assumed to be the product of the weight fraction of the constituent multiplied by the individual heating value of the material. This evaluation presents a matrix of HHV calculated as a function of increasing diversion rates of mixed paper and commingled containers. For the range of diversion rates studied, the overall impact on HHV was shown to be relatively small (less than 50 Btu/lb).

Scalehouse Data – Residential & Commercial Delivery Trends

Relative contributions of residential and industrial, commercial, and institutional (ICI) waste are considered for the Bristol Resource Recovery Facility. Scalehouse data (Figure 4) illustrates relative changes in residential/ICI makeup at the Bristol Facility over a five-year period. Figures 5a and 5b present HHV and monthly precipitation data for both the Bristol and Montgomery County facilities; linear regression analysis for these data points indicate high probability of a linear correlation between HHV and precipitation (r = 0.4247 and 0.4173 respectively with a corresponding probability of a relationship due to chance of less than 0.0005).

FIGURE 5A ROLLING AVERAGE HHV AND PRECIPITATION FOR BRISTOL RESOURCE RECOVERY FACILITY

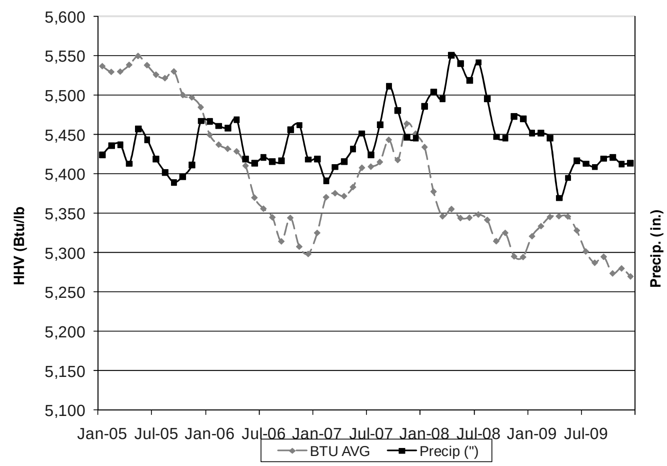
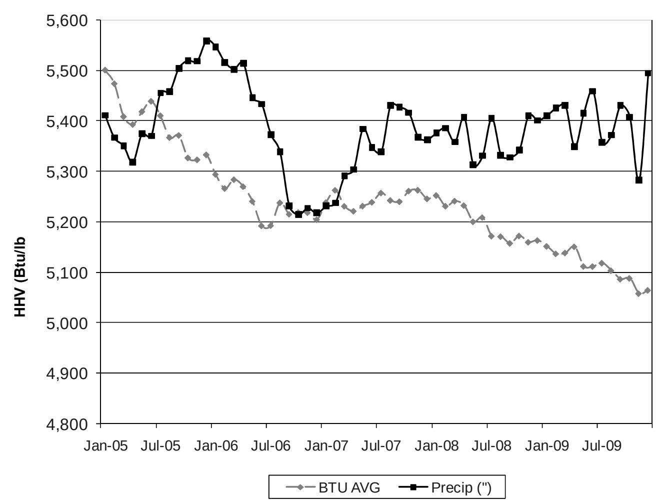


FIGURE 5B ROLLING AVERAGE HHV AND PRECIPITATION FOR NMWDA-MONTGOMERY COUNTY RESOURCE RECOVERY FACILITY



Any attempt to correlate residential/ICI makeup with HHV is complicated by particular and changing patterns in hauler deliveries; for example, the dip in ICI tonnage shown in February 2009 is attributed to a change in practices by one major hauler, and thus, is not representative of the composition of the waste stream. This is corroborated by Table 4, which reports ICI makeup for five Connecticut locations sampled as part of the CTDEP study in 2009, and showing anomalous results for the Bristol facility (ICI comprised of only 23%) compared to the other four study sites (average ICI of 43%).

TABLE 4 FRACTION OF ICI WASTES RECEIVED BY CT FACILITIES

	Residential		ICI	
Facility	Residential Transfer	Packer Loads	Compacted Dropboxes	Packer Loads
Bristol Resource Recovery Facility	37	264	32	60
CRRA Mid-CT	46	566	76	442
CRRA Preston	83	275	55	239
New Haven Transfer Station	0	128	30	70
Wheelabrator Bridgeport	95	408	31	240

Bristol CT Plant Data

Bristol, CT is home to a regional, integrated waste management agency consisting of sixteen central Connecticut municipalities, which includes a mass-burn facility owned and operated by Covanta Energy, as well as curbside residential recycling, household hazardous waste, and electronics recycling programs. Similar to the Montgomery County facility, heating value for the 650 tpd Bristol Resource Recovery Facility is tracked on a monthly basis using the specific steam correlation method developed by Ogden Martin Systems, Inc. (now Covanta Energy).

Tables 5a and 5b compare seasonal waste composition data for both facilities.

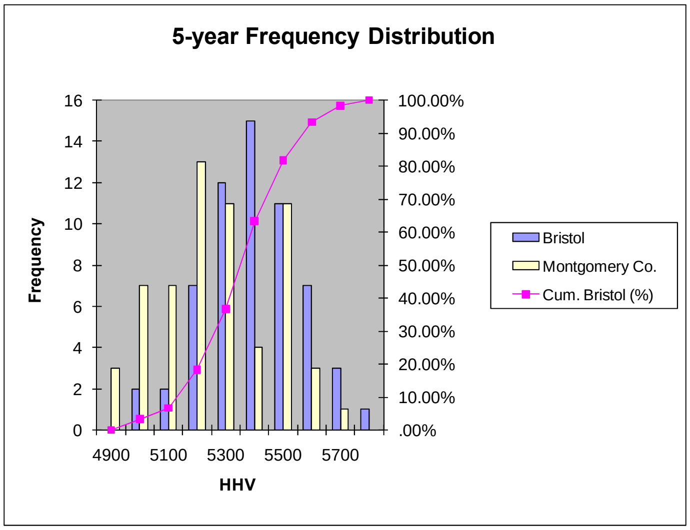
TABLE 5A SEASONAL WASTE COMPOSITION DATA, CT BRISTOL

	Spring 2009				Fall 2009		
Material Group	**Avg**	**Lower**	**Upper**		**Avg**	**Lower**	**Upper**
Paper	31.4%	26.3%	36.5%		22.0%	16.9%	27.1%
Plastic	14.8%	11.8%	17.8%		13.5%	11.5%	15.5%
Metal	4.9%	3.3%	6.5%		5.9%	3.3%	8.5%
Glass	3.9%	0.7%	7.1%		1.5%	0.6%	2.4%
Organics	21.7%	14.1%	29.3%		28.8%	23.0%	34.6%
C&D	11.3%	6.4%	16.2%		16.6%	11.7%	21.5%
HHW	1.0%	0.2%	1.8%		0.4%	0.1%	0.7%
Electronics	1.2%	0.5%	1.9%		1.1%	0.2%	2.0%
Other Wastes	9.6%	6.7%	12.5%		10.4%	6.6%	14.2%
Total	**100%**				**100%**		

TABLE 5B SEASONAL WASTE COMPOSITION DATA, MONTGOMERY COUNTY

	Fall 2008				Spring 2009		
Material Group	**Avg**	**Lower**	**Upper**		**Avg**	**Lower**	**Upper**
Paper	26.7%	25.5%	28.2%		27.3%	26.0%	28.8%
Plastic	14.4%	13.6%	15.1%		14.5%	13.7%	15.2%
Organic	35.6%	33.8%	37.6%		40.4%	38.3%	42.7%
Ferrous Metal	3.5%	2.8%	4.1%		1.7%	1.3%	2.0%
Non-Ferrous Metal	1.3%	1.0%	1.6%		1.2%	0.9%	1.5%
Glass	2.2%	1.8%	2.6%		2.9%	2.3%	3.5%
Wood	6.8%	4.8%	8.7%		3.0%	2.1%	3.8%
Inorganic	4.3%	3.4%	5.0%		4.7%	3.7%	5.5%
Yard Waste	3.4%	2.3%	4.5%		2.7%	1.9%	3.6%
Hazardous	1.9%	1.2%	2.5%		1.7%	1.1%	2.2%
Total	**100%**				**100%**		

FIGURE 6 FREQUENCY DISTRIBUTION FOR BRISTOL AND MONTGOMERY COUNTY RESOURCE RECOVERY FACILITIES



For the Bristol facility, this paper examines waste composition data obtained from the 2009 Connecticut DEP study to derive a representative ultimate analysis following the methods reported by Chang and others. Tables 6a and 6b illustrate the application of an empirical approach to calculating HHV. For the month of February 2009, the steam correlation method yielded a value of 5,461 Btu/lb (3,034 kcal/kg), which compares with the composition study result in Table 6a, which yields 6,438 Btu/lb (3,577 kcal/kg) and is within the limits of precision for this analysis.

TABLE 6A BRISTOL HHV COMPUTATION BASED ON DERIVED ELEMENTAL COMPOSITION

Material		Weight Percent	Relative Moisture %
Paper, Mixed		15.05	1.54
Newsprint		4.05	0.24
Brown Paper		0.50	0.03
Trade Magazine		1.55	0.06
Corrugated Boxes		5.55	0.29
Vegetable Food Waste		14.80	11.59
Mixed Garbage I		9.05	6.52
Green Logs		1.80	0.90
Demolition Softwood		6.55	0.50
Lawn Grass I		7.55	5.68
Brush		0.65	0.26
Polyethylene		2.25	0.00
Polystyrene		0.90	0.00
Polyvinyl Chloride		0.45	0.00
Ashes		0.50	0.05
Glass		4.10	0.08
Plastics		6.00	0.90
Plastic film		4.55	0.00
Textiles I		0.70	0.00
Textiles II (Magrinho)		8.45	0.85
Ferrous		4.55	0.00
Non-ferrous		0.45	0.00
Total		**100.00**	**29.50**
	Component	**Weight Fraction**	
	C	48.87%	
	H	6.49%	
	O	31.16%	
	N	1.09%	
	S	0.13%	
	Ash	11.95%	
	Cl	0.31%	
	Total	**100.00%**	
Mixed Waste Heating Value (Btu/lb) =			***6,438***

Similarly, for Montgomery County the same approach is used to compare monthly HHV (Steam Correlation Method) compared to waste composition data extrapolated to ultimate analysis, and then calculating a heating value. For the months of November 2008 and June 2009, the steam correlation method yielded a value of 5,152 Btu/lb (2,861 kcal/kg) as compared with the composition study result in Table 6, 6,253 Btu/lb (3,474 kcal/kg). Thus for both Bristol and Montgomery comparisons of HHW calculated using the derived elemental composition, we observed higher predicted values than reported by the steam correlation method. This result is consistent with observations noted above with respect to moisture loss during sampling (see Table 3).

TABLE 6B MONTGOMERY COUNTY HHV COMPUTATION BASED ON DERIVED ELEMENTAL COMPOSITION

Material		Weight Percent	Relative Moisture %
Paper, Mixed		16.27	1.67
Newsprint		5.62	0.34
Trade Magazine		1.91	0.00
Corrugated Boxes		2.81	0.08
Plastic-Coated Paper		0.40	0.15
Waxed Milk Cartons		0.00	0.02
Vegetable Food Waste		19.68	0.00
Mixed Garbage I		14.06	15.41
Demolition Softwood		4.92	10.12
Lawn Grass I		1.00	0.38
Brush		1.00	0.76
Mixed Greens		1.00	0.40
Polyethylene		1.91	0.62
Polystyrene		1.31	0.00
Ashes		3.92	0.00
Glass		2.61	0.00
Plastics		4.42	0.39
Plastic film		6.73	0.05
Textiles II (Magrinho)		6.53	0.66
Ferrous		2.61	0.00
Non-ferrous		1.31	0.65
Total		**100.00**	**31.70**
	Component	**Weight Fraction**	
	C	49.06%	
	H	6.39%	
	O	29.97%	
	N	0.96%	
	S	0.14%	
	Ash	13.48%	
	Cl	0.00%	
	Total	**100.00%**	
Mixed Waste Heating Value (Btu/lb) =			***6,253***

When examining the sensitivity of non-metal items to assumed moisture content, variations in moisture alone can account for differences of 1,000 Btu/lb. Moisture content and sampling are discussed above with respect to U.S. experience, and sampling results reported by Chang et. al. for moisture show relative error of 10% or more for Taiwan waste. In order to reduce the sensitivity of calculated heating values to moisture content, some authors recommend much greater emphasis on LHV.[26,27]

Each of the respective methods for estimating HHV (Chang formula based on Ultimate Analysis and Specific Steam Correlation Method) mask underlying broad assumptions which significantly influence the outcome. Table 7 highlights the nature of these assumptions, along with an estimate of the expected range of error, where known; for purposes of deriving HHV from waste composition data, sample size (number of samples and size of individual sample) are important, but not easily ascertained in advance of the study.

For the variety of materials considered (food waste, brush, and "organics"), a relative error of nearly 30% is probably reasonable. A larger sample size does not guarantee a more precise result if the material is inherently variable.

TABLE 7. METHODS FOR INDIRECT MEASUREMENT OF HHV AND ASSOCIATED UNCERTAINTY

METHOD P	ARAMETER	SOURCE OF ERROR	UNCERTAINTY
Chang, Dulong, Meraz, Channiwala, others	Ultimate Analysis	Relating waste type (e.g., paper, organics, inerts) to elemental composition	Literature reports uncertainty as low as 1.5%, however studies rely on relationships between composition and ultimate analysis which have not been verified in the past decade
	Sample size	Too few samples or sample size too small	See discussion regarding *Organics*
	Elemental composition	Does not account for manufacturing, technology changes	Unknown
	Moisture	Reported values may deviate significantly from as-received	Relative error > 10%[6]
Specific Steam Correlation	Waste input	Imprecise month-end inventory; differences in stacking	Est. > 4%
	Steam flow	Instrument error (orifice meter)	Est. 5%
	Flue gas moisture content	No adjustments made in calculation for moisture differences	
	Excess air	Relatively small adjustments to formula are made with wide variation in excess air, potentially ignoring widely varying boiler efficiencies	Unknown
	Heat transfer	Variations in heat transfer surface area, impact of inconel cladding	Unknown
	Unburned carbon	Factored into the underlying SSR correlation, but not periodically sampled	> 200 Btu/lb depending upon combustion conditions and controls
	Change in waste composition	Relies on assumed constancy of C:H elemental composition	1% change in H content yields 300 Btu/lb change in theoretical HHV

CONCLUSIONS

Understanding the composition of waste is critical to professionals in the field. There are important implications for resource recovery facilities, especially for combustion parameters such as design heat transfer surface area, combustion air flow, fan sizing, and ash quantity and makeup. A number of algorithms are utilized to indirectly measure HHV (i.e. methods other that ASTM PTC 34), and in this paper, the authors describe comparisons of the Specific Steam Correlation Method with calculations based on ultimate analysis derived from waste composition studies. These surveys yield information otherwise difficult to obtain data, such as waste moisture content. They also provide useful metrics for determining the relative success of recycling and waste diversion programs. Food waste composting initiatives, such as the mandatory San Francisco program, have the potential to markedly influence waste characteristics. The meteoric increase in use of electronic devices also will impact management strategies, and ultimately the success of these diversion efforts will factor into the characteristics of waste destined for recycling, disposal or energy recovery.

During 2008 and 2009, fundamental changes in the U.S. economy undoubtedly contributed to shifts in waste composition. This study offers no broad conclusions as to whether major changes were observed in recent waste composition studies, due to limitations in the number and size of samples, differences in nomenclature used to classify materials, and other factors. On the other hand, large-scale comprehensive reviews, such as the bi-annual USEPA Municipal Solid Waste in the United States – Facts and Figures, may be overly generalized, providing relatively minor value to those responsible for regional waste management programs. Thus, we can look to analyses of waste composition and heating value to observe developing trends and draw inferences about the makeup of the various constituents of the waste stream, and the data are especially valuable when matched with other metrics used to describe properties of MSW.

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