University of New Hampshire Life-Cycle Assessment of C&D Derived Biomass/Wood Waste Management

Prepared by:

Jenna Jambeck
Research Assistant Professor

Alberta Carpenter
Research Assistant

Kevin Gardner
Director, Environmental Research Group

Environmental Research Group
University of New Hampshire
Durham, NH

Keith Weitz
RTI

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EXECUTIVE SUMMARY

A large portion (43%) of construction and demolition (C&D) debris is diverted from landfills in New Hampshire (NH). The diversion typically takes place at mixed C&D processing facilities that separate out usable fractions of the material such as metal, aggregate, and wood products. These products have various beneficial uses which divert them from landfill disposal. To provide assistance in quantifying trade-offs for the management of wood construction scraps/C&D waste wood in New Hampshire, UNH conducted a life-cycle assessment (LCA) of various management options using the U.S. Environmental Protection Agency's Municipal Solid Waste Decision Support Tool (MSW DST). Adjustments to the MSW DST were made to more accurately model the management of C&D debris and C&D wood. The metal concentration of the C&D wood product was increased, as well as the energy (BTU) content. Details of how the MSW DST was modified are contained in Section 2.

Seven different management scenarios were considered based upon the annual production of C&D debris in the state of New Hampshire, 702,000 tons (see Section 3). Additionally, a scenario was developed to compare the combustion of virgin wood from northern New Hampshire with locally produced C&D wood. The virgin wood is transported a distance of approximately 150 miles, the energy generated offsets the northeast power grid and the ash is beneficially used (not landfilled). The tonnage used for this comparison is 280,000 tons of wood, based upon the annual production of C&D wood in New Hampshire.

For the first set of comparisons, results were obtained for energy consumption, carbon emissions, criteria air pollutants, ancillary solid waste produced, and organic and inorganic constituents in water (details contained in Section 4). LCA illustrates trade-offs through examining impacts and benefits. Negative results illustrate the "offsetting" of a quantity of emissions. Not only do negative results mean that emission of this constituent is avoided, it conceptually means that this constituent is reduced below what is currently being released. For example, negative carbon emissions, would result in carbon credits (that may eventually be able to be sold as long as they are considered in renewable portfolio standards).

As shown in the results section (Section 4), the recycling facility along with combustion of wood with energy recovery and offsetting either the northeast energy grid or coal result in benefits and offsets. In the outranking of scenarios, all scenarios with wood waste combustion with energy recovery had lower impact rankings than the others. The recycling-only scenarios resulted in less overall impact than the disposal-only scenarios. While for the disposal scenarios, the landfill gas-to-energy scenario has more offsets than the flared landfill gas. This ranking indicates which scenario provided the lowest impacts most frequently, which in this case, was the scenario with C&D debris recycling and local combustion of the wood derived product with energy recovery.

The benefits afforded by C&D recycling and combustion of the wood fraction for energy production have significant ramifications. For example, recycling C&D debris and combustion of C&D wood with energy recovery produces a net gain in energy of 7,000,000 MBTU – enough to power 191,000 homes for one year in New Hampshire. Similarly, 70,000 to 130,000 tons of carbon emissions are eliminated; 130,000 tons of carbon equivalent emissions are approximately equal to the annual carbon emissions from the electricity used by 55,000 households (using EPA's Greenhouse Gas Equivalency Calculator). Criteria air pollutants are significantly reduced as well when combusting C&D wood with energy recovery producing 600 tons/yr less particulate matter, 430 tons/yr less of nitrogen oxides, 2,300 tons/yr less of sulfur oxides, 890 tons/yr less of carbon monoxide and 10 pounds/yr less of lead (with northeast power grid off-set) when compared to landfilling.

When C&D wood combustion was compared with virgin wood combustion, it was found that C&D wood combustion had lower impacts. While combustion of virgin wood and C&D wood both produce energy, the C&D wood combustion produces over 1.2 million MBTU more energy for the same amount of wood (280,000 tons) when compared to virgin wood combustion with energy recovery. This is enough extra energy to power over 33,000 homes for one year. Additionally the carbon offsets are higher for C&D wood – by 16,700 metric tons of carbon equivalents (like taking 11,000 passenger cars off the road for 1 year). Based upon best available air pollution technologies and a wood tonnage of 280,000/yr, the C&D wood used for energy production produces: 50 tons/yr less particulate matter, 200 tons/yr less of nitrogen oxides, 485 tons/yr less of sulfur oxides, and 69 tons/yr less of carbon monoxide when compared to virgin wood. Additionally, it results in a reduction of lead emissions, over 9 lb only ~1.5 different than virgin wood.

It is clear from the results of this assessment that C&D recycling facilities provide many environmental benefits to the state of New Hampshire and combustion of C&D wood also has significant additional benefits. Many of the off-sets discussed in this report come from the fact that the wood is a source of energy and it offsets traditional energy sources when it is used for energy production. Both virgin and C&D wood can be considered biogenic alternative energy sources. The use of alterative energy sources will likely continue to increase and this analysis illustrates that C&D wood waste can contribute to an integrated alternative energy portfolio.

1.0 INTRODUCTION

In order to quantify the environmental impacts associated with the various options for management of wood construction scraps/C&D waste wood in New Hampshire, UNH conducted an analysis of various management scenarios. In order to ensure a holistic approach, a life cycle assessment approach employing the U.S. Environmental Protection Agency's Municipal Solid Waste Decision Support Tool (MSW DST) was used. There are several management options when wood waste material is produced: reuse, recycling, combustion with energy recovery, and landfilling. The U.S. EPA hierarchy states generally that waste should be managed in the order just described when possible (US EPA, 2007a). New Hampshire has also codified this waste management hierarchy as RSA 149-M:3: 1) reduce the generation of wastes, 2) reuse and recycle, 3) compost, 4) convert wastes to energy, and 5) landfill. This hierarchy was designed to conserve landfill space by reducing the amount of waste generated, maximizing recycling and composting, and reducing volume by combustion, as well as creating energy that can reduce dependence on fossil fuels. There are additional ways of examining waste management choices. LCA is an approach that enables quantification of impacts from and trade-offs between various waste management options.

LCA is a method of assessing environmental impacts associated with a product or process over its entire life, from "cradle to grave". The method involves breaking down the product or process into separate systems (materials extraction and processing, production, transportation, use, disposal, etc) and compiling an inventory of inputs and outputs for each system. The impacts associated with those inputs and outputs are evaluated for potential environmental impacts and interpreted relative to the objectives of the study. The life cycle assessment method is standardized in ANSI/ISO 14040 (1997).

With carbon emissions and climate change as significant as it is today, the waste management hierarchy has become even more important. The Intergovernmental Panel on Climate Change (IPCC) has released portions of their Fourth Assessment Report: Working Group I: The Physical Science Process (IPCC, 2007a), Working Group II: Impacts Adaptation and Vulnerability (IPCC, 2007b), and Working Group III: Mitigation of Climate Change (IPCC, 2007c). These reports justify concern for greenhouse gas emissions and provide some mitigation strategies. Working Group III has recommended the waste sector examine methane recovery from landfills, combustion with energy recovery, composting of organic waste, controlled wastewater treatment, recycling and waste minimization (IPCC, 2007c). It is likely that a combination of these options will provide for the most greenhouse gas mitigation.

The generation of carbon dioxide from wood (in either a landfill or combustion facility) is considered "carbon neutral." As CO_2 emissions are released, forests are taking up similar amounts of CO_2 (this is on a different time scale than the millions of years needed to make fossil fuels from carbon sources). This relatively quick cycling of carbon means the CO_2 emissions from the combustion or landfilling of wood are not often counted in climate change calculations. This is the case in the most current US EPA GHG report (US EPA, 2007b). It states the following, "*The combustion of biomass and biomass-*

based fuels also emits greenhouse gases. CO_2 emissions from these activities, however, are not included in national emissions totals because biomass fuels are of biogenic origin. It is assumed that the carbon released during the consumption of biomass is recycled as U.S. forests and crops regenerate, causing no net addition of CO_2 to the atmosphere." The IPCC does not count CO_2 emissions from wood combusted for energy or produced from landfills for inventory proposes (although it can be included for QA/QC purposes as a note) (IPCC, 2006).

While combustion of wood is considered carbon neutral and produces negative emission when accounting for the off-setting of fossil fuel energy, the IPCC in its most recent summary report released states that wood combustion with energy recovery and carbon dioxide capture would provide a method of reducing global atmospheric carbon levels (IPCC, 2007c). An additional benefit to landfilling combusted wood as opposed to uncombusted wood is the reduction in land use area needed. Ash takes up 80 to 90% less space in landfills, which means less leachate production and more airspace preserved for future disposal. Land use and conservation also has carbon off-set implications as forested and undisturbed land sequesters carbon as well.

C&D derived biomass/wood (from here on out referred to as 'C&D wood') is comprised of primarily wood (>85%), with other inert materials found in C&D contributing a small fraction. Additionally, air pollution technologies exist to combust the wood derived from C&D debris with emissions below state and federal air regulations (best available control technologies [BACT]). Scientific data shows that emissions from the facilities permitted to burn C&D wood in the state of Maine are within state and federal air pollution control limits (NESCAUM, 2006). The growth of crops/forest specifically for combustion is a form of wood fuel; however, for C&D wood, the wood is processed for use construction and either becomes scrap from the construction process or used in a building before combustion. Carbon is stored in the wood product while it is in use. Combustion of the wood can take place at the end of the wood's life cycle as shown in Figure 1. Two literature sources have documented the benefits of combusting C&D debris wood in the U.S. and in Florida (Jambeck et al., 2006; Cochran, 2006). Both sources illustrated lower emissions of carbon dioxide and a net gain in energy (as opposed to energy use) when compared with other recycling opportunities and landfilling.

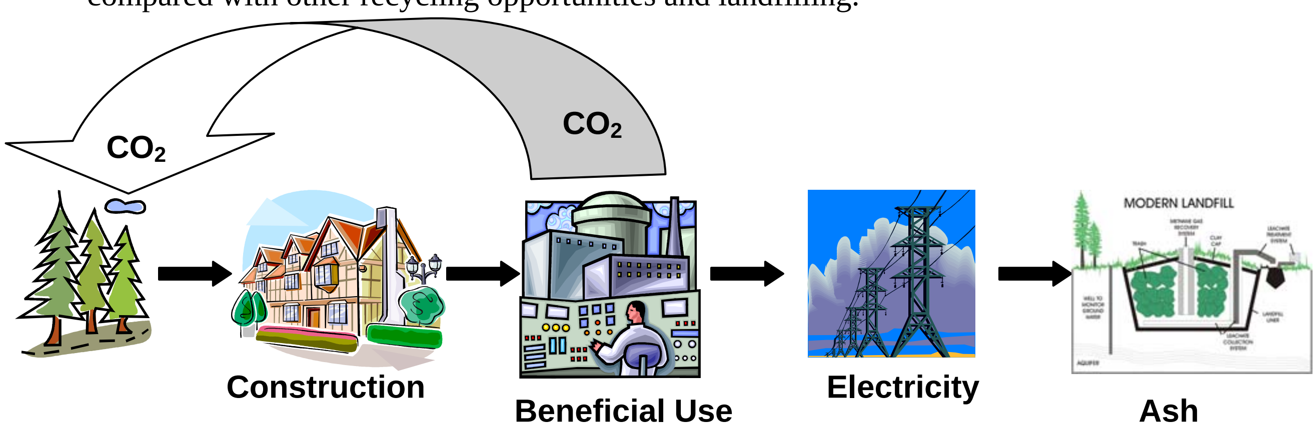

Figure 1. Life-cycle of wood used in construction and in combustion with energy recovery

While this introductory information and the literature review previously conducted by UNH (Jambeck et al., 2007) provides a general idea of the kind of trade-offs one would expect to find in a C&D wood management scenario, a full analysis would be influenced by other factors including landfill gas to energy, C&D processing, and transportation. For this reason, a site-specific LCA was conducted for C&D debris in New Hampshire, with a specific focus on C&D wood management.

This report documents the LCA conducted for New Hampshire-specific management scenarios. Section 2 of the report provides an overview of the U.S. EPA's Municipal Solid Waste Decision Support Tool and how this tool was utilized for the analysis. Section 3 describes the scenarios developed and input into the MSW DST. Section 4 presents the results and Section 5 contains a summary.

2.0 MUNICIPAL SOLID WASTE DECISION SUPPORT TOOL (MSW DST)

The municipal solid waste decision support tool (MSW DST) is a linear programming (LP)-based decision model to aid in identifying environmentally and economically efficient strategies for integrated MSW management (Solano et al., 2002a; Solano et al., 2002b). The tool was developed by the U.S. Environmental Protection Agency's (U.S. EPA) National Risk Management Research Laboratory (NRML) in cooperation with RTI International (located in Research Triangle Park, North Carolina) and North Carolina State University (NCSU). Environmental and economic aspects for hypothetical integrated solid waste management alternatives are estimated using LCA and full-cost accounting methodologies, respectively (Weitz et al., 1999). The MSW DST provides a quantitative comparison of many aspects taken into consideration when waste management decisions are made including cost and many environmental parameters such as emissions of carbon monoxide (CO), carbon dioxide (CO_2) (both wood and fossil fuel derived), nitrogen oxides (NO_x), sulfur oxides (SO_x), total particulate matter (PM), carbon equivalents (MTCE), energy consumption and metals released into the environment. The model bases calculated emissions on the entire waste management system including waste collection, transportation, recycling, treatment, and disposal (Thorneloe and Weitz, 2004).

The holistic nature of this model made it a useful tool in comparing the environmental impacts resulting from the management of wood waste in New Hampshire. Since the model is not yet commercially available, input data was supplied to RTI International. The MSW DST was run at RTI with results in Excel provided to UNH. UNH then completed data analysis and interpretation.

The MSW DST contains life-cycle environmental data for waste collection, transport, recycling, composting, waste-to-energy combustion (WTE) and landfilling; for the production and consumption of energy for the U.S. national and regional grids; and for the production of aluminum, glass, paper, plastic, and steel (Thorneloe and Weitz, 2004). Although the MSW DST contains large quantities of life-cycle inventory data that has been extensively documented (US EPA, 2003), details on the important and influential life-cycle inventory data relative to this analysis are described in this section.

2.1 Landfill Disposal

When wood (represented by "branches") is disposed in a landfill, the degradation of the wood results in methane production. The methane emission value for the disposal of branches utilized by the MSW DST is 62.6 ml/dry g of wood (Eleazer et al., 1997). While wood has been shown to release some carbon (as methane and carbon dioxide) in landfill environments, data supports the point that little degradation of wood actually occurs under anaerobic conditions (Eleazer et al., 1997; Barlaz, 2004). It has been found that even though cellulose and hemicellulose break down in landfill environments, the lignin content in wood (which has been shown to not degrade in anaerobic conditions) encapsulates the cellulose and hemicellulose such that it cannot effectively be degraded

(Barlaz, 2004). For this reason, the MSW DST uses a value for methane generation from the specific wood component and not overall landfill methane potential (e.g., such as LandGEM landfill gas estimation). The methane potentially generated, and counted as an off-set by the disposed material in this case, is only the result of wood decomposition. The MSW DST can model landfill gas management by venting, flaring or gas-to-energy. In this case, since the material being disposed is only wood or C&D debris, landfill gas-to-energy would not likely be appropriate; however, since a C&D-only landfill does not exist in NH, it is likely that disposed material would be mixed with MSW resulting in a contribution of the material to a landfill gas (LFG) stream that could be beneficially used. The landfilling of the ash material is also incorporated by the MSW DST, although gas is not produced. The MSW DST also includes the impacts from landfill construction, operation, any leachate and gas produced by the various landfills included in each management scenario.

2.2 Air Emissions

The combustion scenarios assume the air pollution control systems in all the combustion facilities are in compliance with U.S. and New Hampshire requirements, which is a realistic assumption according to previously reviewed literature on the combustion of C&D debris wood (NASCAUM, 2006; Humphrey, 2005). For example, this means that a certain percentage of the metals in the incoming C&D wood are converted to air emissions and then removed by air pollution control systems at realistic efficiencies shown in Table 1.

Table 1. Default Metal Removal Efficiencies in the MSW DST[1]

Metal	% Removal
Arsenic	99.90%
Boron	76.50%
Cadmium	99.70%
Chromium	99.30%
Copper	99.60%
Mercury	92.70%
Nickel	96.60%
Lead	99.80%
Antimony	96.70%
Selenium	92.90%
Zinc	99.70%

[1]Source: RTI Background document https://webdstmsw.rti.org/

The carbon emissions in both the landfill and combustion models are from wood, thus biogenic and, although counted by the model, are given a zero weight when calculating carbon equivalents. Offsets of carbon emissions can result from the displacement of fossil fuels from energy production and materials recycling/reuse, which off-set the need for mining virgin materials (resulting in less carbon emissions). Carbon emissions in units of tons are calculated in the model as illustrated by Equation (1).

$$\frac{[FossilCO_2 + (CH_4)(21)]\frac{12lbC}{44lbCO_2}}{2000lb/ton} \qquad (1)$$

Two scenarios for the off-set of electrical power were considered. The northeast power grid was used to calculate the off-set values for the applicable scenarios, and since C&D wood could replace coal at a coal-fired power plant, one scenario used an off-set for 100% coal. The values in the MSW DST for the northeast energy grid consist of the percentages of energy production shown in Figure 2.

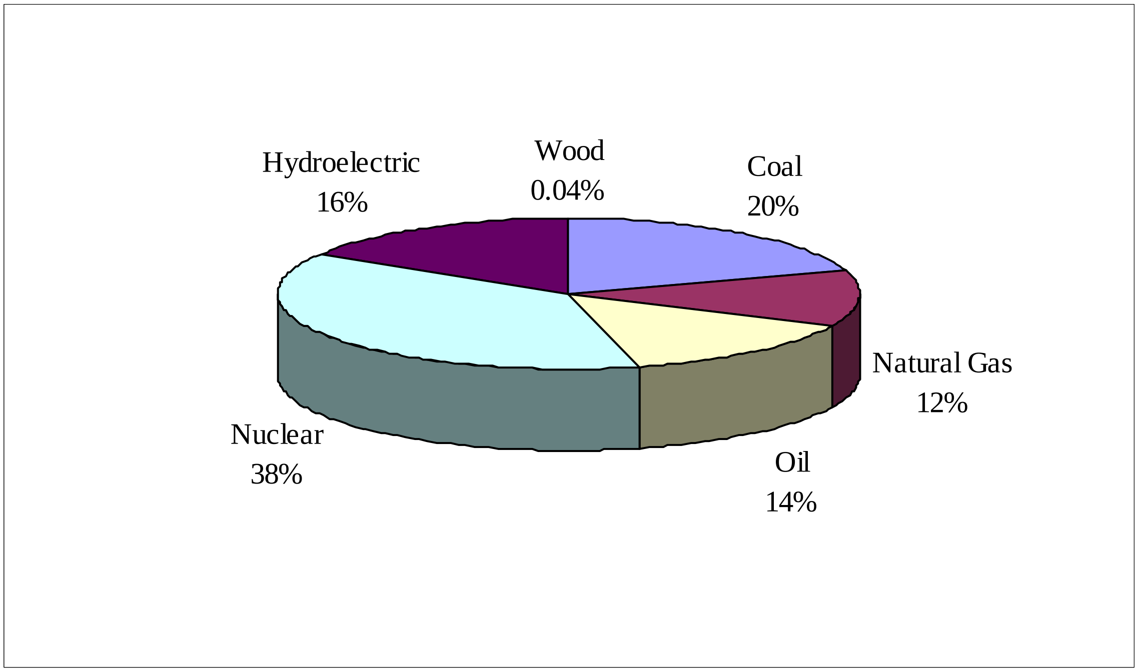

Figure 2. Northeast Power Grid Distribution
([1]Source: RTI Background document https://webdstmsw.rti.org/)

2.3 MSW DST Input Values for New Hampshire C&D Debris

The MSW DST model contains a wood material characterized as “branches.” This material is representative of virgin wood material combusted with energy recovery or disposed in a landfill. However, in order to more correctly represent C&D wood, various characteristics of the “branches” were changed. First the metal content of the branches was adjusted to better represent the metal content observed in C&D wood. The default values in the MSW DST used for virgin wood and the new input values for C&D wood (both total and volatile metal content) are shown in Table 2. The volatile metal content was calculated based upon the methodology outlined in an internal RTI document provided in Appendix A. Although this table contains numerous metal values, only lead is used in air emissions calculations by the MSW DST. Additionally, these values are not the actual emissions produced by the combustion facilities, but the input values to which the air pollution control efficiencies are applied.

Table 2. Metal Content of Virgin and C&D Wood used in the MSW DST (quantities *before* air pollution efficiencies are applied)

Metal	Default Value in MSW DST (used for virgin wood) (lb/ton combusted)	Total Metal Content for C&D Wood (lb/ton)[1]	Value used for C&D Wood (lb/ton combusted)[2]
Arsenic	3.17E-06	7.39E-02	1.30E-04
Boron	5.45E-04	NA	NA
Cadmium	2.68E-04	1.29E-03	1.57E-04
Chromium	2.61E-04	1.10E-01	1.10E-01*
Copper	1.93E-05	6.44	6.44*
Mercury	3.94E-04	2.61E-04	1.28E-04
Nickel	3.66E-04	NA	NA
Lead	6.51E-03	5.17E-01	2.72E-02
Antimony	6.87E-05	NA	NA
Selenium	1.50E-07	BDL	BDL
Zinc	5.75E-03	NA	NA

[1]The total metal values for C&D wood are the metal content based upon 10 samples. Data provided by Green Seal Environmental, 2007. [2]Some metal content would not volatilize. Volatilization percentage based upon method outlined in internal RTI document, see Appendix A and/or https://webdstmsw.rti.org/ for details. *No volatilization factor available, so total metal content used. NA=Not Available, BDL=Below Detection Limit: virgin wood values used.

The combustion plant heat rate used in the model for both virgin and C&D wood scenarios is 13,100 (BTU/KW-hr), based upon a facility combusting virgin wood in New Hampshire (Public Service New Hampshire (PSNH), 2007). While this heating value is lower (therefore more efficient) than typical waste combustion facilities, the facility is an advanced retrofit of a coal-fired power plant, containing a fluidized-bed boiler that circulates wood chips combusting them while suspended in air within the combustion chamber. According to PSNH, this process burns fuel more completely. It is assumed that new facilities coming online to combust both C&D wood and virgin wood would be similar.

The BTU/pound value of C&D wood is higher than that of virgin wood. This difference is primarily because of the difference in moisture content between C&D wood and virgin wood material. The BTU values and ultimate analysis for the two different wood materials are given in Table 3. Because of the lack of real emissions data for combusting 100% C&D wood, the default values in the model for branches (i.e., virgin wood) were used for the non-metalic air pollutants include in the model: sulfur dioxides (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), and hydrochloric acid (HCL).

Using the default values for branches for criteria pollutants, including dioxins/furans in the model is valid and likely conservative. The Northeast States for Coordinated Air Use Management (NESCAUM) summarized experiments conducted at the University of

Maine on the combustion of C&D wood at three facilities burning C&D wood in Maine (NESCAUM, 2006). Testing included 100% clean wood, 90% clean wood with 10% C&D wood and pentachlorophenol (PCP)-treated wood, and 50% C&D wood and 50% PCP-treated wood. In all cases the stack emissions during the trial burns were far below Maine's ambient air guidelines and New Hampshire stack emission limits (Humphrey, 2005; NESCAUM, 2006). Additionally, a facility with an advanced air pollution control system combusting 10% C&D wood mixed with virgin wood had lower dioxin emissions than a facility combusting 100% virgin wood. Furthermore, the levels of arsenic and dioxin emissions were well below levels found at municipal solid waste combustors and below all applicable regulations (Humphrey, 2005; NESCAUM, 2006). The report by NESCAUM also provides details of a recent Best Available Control Technology (BACT) analysis in Maine. The analysis shows that the proposed BACT levels for C&D wood fuel combustion are lower than limits imposed on coal, virgin wood, and oil fired power plants (Humphrey, 2005; NESCAUM, 2006). This literature indicates that with advanced pollution control systems, emissions could be less from facilities burning C&D wood instead of these other fuels.

Table 3. Ultimate Analysis of Virgin Wood and C&D Wood Product

	Default Value in MSW DST (used for virgin wood)	Value used for C&D Wood[2]
Moisture (%)	45%	12.4%
Carbon (%)	23.3%	43.3%
Hydrogen (%)	2.9%	4.75
Nitrogen (%)	0.9%	0.4%
Sulfur (%)	0.2%	0.2%
Ash (%)	10.1%	6.9%
Oxygen (%)	17.5%	32.0%
BTU/lb	4,500[1]	7,380

[1]PSNH, 2007 (also the average reported by Tchobanoglous et al., 1993)
[2]Values based upon 10 samples. Data provided by Green Seal Environmental, 2007

The tonnage of material put through the model is based upon the <u>2006 estimated quantity of C&D debris generated in New Hampshire, which was 702,000 tons</u> (NH DES, 2007). The characterization of this material is given in Figure 3. The total tonnage of C&D debris (702,000 tons) was put through the various scenarios outlined in Section 3. When the processing facility was included in a scenario, an 83% efficiency was used (NH DES, 2007), resulting in 17% (119,000 tons) of the debris being landfilled. Forty percent of the C&D debris consists of wood (280,000 tons), which was put through different management options after it left the processing facility (for scenarios that included processing), cardboard and metals were recycled, with the remaining materials being reused. Since the annual tonnage of C&D material was used as the input, the impacts and off-sets associated with the results are total quantities on an annual basis.

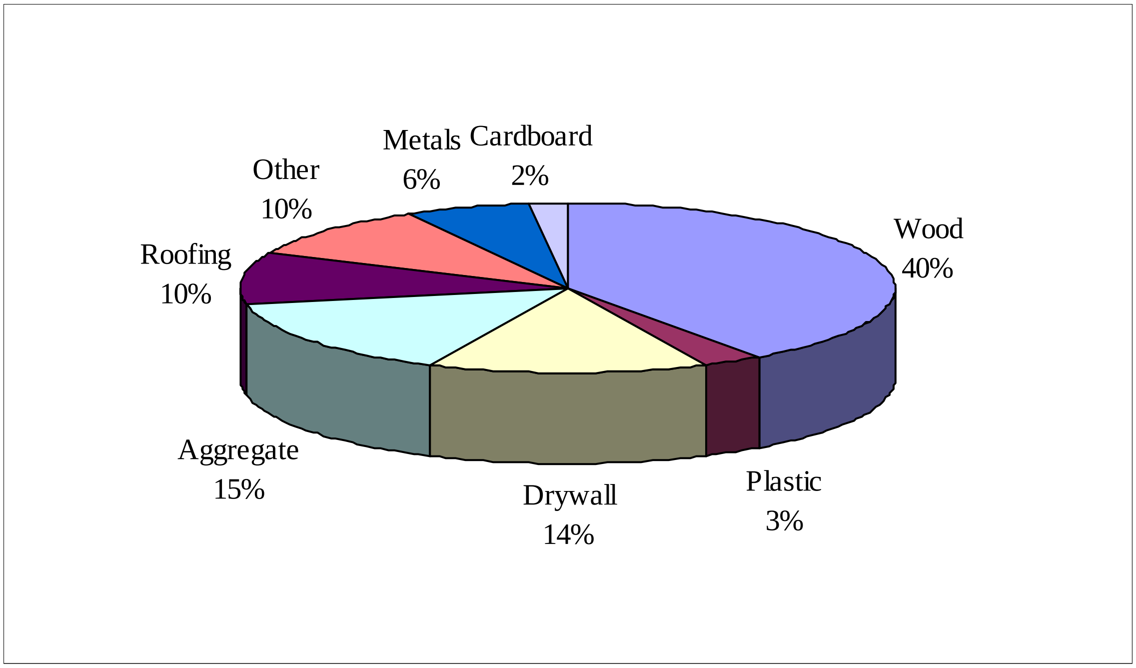

Figure 3. Characterization of C&D Debris in New Hampshire (NH DES, 2007)

2.4 Assumptions and Limitations

Although all attempts were made to modify the MSW DST to conduct this analysis as accurately as possible, it should be noted that the MSW DST assumes that the energy recovery combustion facilities adhere to state and local air regulations. Although the scenarios include the life cycle data for a materials recovery facility processing C&D materials, the scenarios do not include the chipping of C&D wood or virgin wood. Secondly, C&D wood is typically greater than 90% wood; however, since the C&D debris waste stream is heterogeneous and the non-wood fractions vary in composition, the C&D wood fraction only was used as the input for combustion in the MSW DST for this analysis. Additionally, processed C&D wood is currently produced per fuel specifications in Maine, which require less than 1% plastics and less than 1% non-combustibles. These other components of C&D wood (less than 10%) may affect the results if the materials create energy (would increase energy offsets) or contain fossil fuels (may decrease carbon offsets). It is not known if these other components would contain metals contributing to air emissions. Lack of some of this information illustrates that further research on actual feedstock characteristics of C&D wood data is needed.

3.0 NEW HAMPSHIRE LCA C&D WOOD WASTE MANAGMENT SCENARIOS

All scenarios begin with the assumption of a 25 mile (local) transport distance to the processing or disposal facility (no other collection is taken into account). All of the scenarios model some form of management of C&D debris, except for Scenario 8, which models the transport and combustion of virgin wood from Northern New Hampshire for a comparison with the energy recovery combustion of C&D wood. Further details on each scenario are given in this Section along with a summary of the scenarios for further comparison in Table 4.

Scenario 1
Scenario 1 models the impact of processing C&D debris at a mixed C&D recovery facility, allowing the recovery of the wood component. The wood fraction is then transported to combustion with energy recovery facilities in Maine or Canada (with an average transport distance assumed to be 140 miles). The energy generated by the combustion of the C&D wood offsets energy otherwise generated by the NE power grid and the wood ash generated is disposed of in an ash landfill.

Scenario 2
Scenario 2 is identical to Scenario 1 except that the combustion with energy recovery is local to NH and assumed to be located at a 25 mile transport distance from the C&D recycling facility. (At 115 miles less than Scenario 1 and assuming 25 tons/trip transporting 280,000 tons of wood/year, the difference from Scenario 1 would equate to a savings of 2,576,000 miles/year. Furthermore, assuming 6 mpg of diesel fuel at $3/gal, it could equate to a savings of approximately 429,333 gal/yr of diesel fuel and $1,288,000/yr).

Scenario 3
Scenario 3 is identical to Scenario 2 except the energy generated offsets 100% coal power only, instead of the power distribution of the northeast power grid. This represents the energy recovery combustion of the C&D wood offsetting the power generated at the coal power fired plants in New Hampshire

Scenario 4
Scenario 4 models the impact of processing C&D debris at a mixed C&D facility as in scenarios 1-3. The wood fraction is then transported and disposed in a local (25 miles) landfill along with the residuals. The LFG potentially generated by the C&D debris (wood fraction is the only fraction to produce methane) decomposing in the landfill is flared.

Scenario 5
Scenario 5 is identical to scenario 4 except that the LFG generated by the C&D wood is used for energy production.

Scenario 6

Scenario 6 models the impacts of no C&D debris separation, processing or recycling. All C&D debris is disposed in a landfill 25 miles away. The landfill gas generated from the C&D debris is flared.

Scenario 7
Scenario 7 is identical to scenario 6 except that the LFG generated by the C&D debris is used for energy production.

Virgin Wood Scenario
This scenario models the combustion with energy recovery of virgin wood collected from harvesting operations in northern New Hampshire (at a distance of 150 miles). The energy generated is offset from the northeast power grid and the ash is used for some beneficial use application. In this case, to compare to a ton-to-ton basis for C&D wood, the tonnage put through the model is 280,000 tons, equal to the amount of C&D wood generated annually in NH. This scenario was also compared to the combustion with energy recovery and landfilled portions of C&D wood management, which consisted of 280,000 tons, for consistency. Neither the energy used nor the environmental implications of the production of the virgin wood (logging, chipping) is considered in this analysis.

Table 4. Summary of Scenarios Input in MSW DST for NH C&D Wood Waste LCA

Scenario	Collection Route[1]	Transport (miles)	Recycling/Transfer	Wood Fuel Transport (miles)	Treatment	Off-set	Disposal
1	None	25	All materials sent to C&D recycling facility (83% recycled, 17% landfilled with flare)	ME/CAN (140mi)	Combustion with energy recovery (C&D wood only)	northeast Grid	Ash LF (10mi)
2	None	25	All materials sent to C&D recycling facility (83% recycled, 17% landfilled with flare)	Local (25mi)	Combustion with energy recovery (C&D wood only)	northeast Grid	Ash LF (10mi)
3	None	25	All materials sent to C&D recycling facility (83% recycled, 17% landfilled with flare)	Local (25mi)	Combustion with energy recovery (C&D wood only)	100% Coal	Ash LF (10mi)
4	None	25	All materials sent to C&D recycling facility (83% recycled, 17% landfilled with flare)	Local (25mi)	None (all landfilled)	None	C&D Wood – landfilled with flare
5	None	25	All materials sent to C&D recycling facility (83% recycled, 17% landfilled with flare)	Local (25mi)	None (all landfilled)	None	C&D Wood – landfilled w/energy recovery
6	None	25	None	None	None (all landfilled)	None	All tonnage – landfilled with flare
7	None	25	None	None	None (all landfilled)	None	All tonnage – landfilled w/energy recovery
VW[2]	None	None	None	From Northern NH (150mi)	Combustion with energy recovery (virgin wood)	northeast Grid	Beneficial use

[1]Collection route not considered since C&D not regularly collected like municipal solid waste. 25 mile transport distance considered from incoming C&D debris to recycling facility. [2]VW=Virgin Wood Scenario

4.0 RESULTS

Since the 2006 C&D debris tonnage was used as an input into the MSW DST, the impacts and off-sets associated with the results are total quantities on an annual basis. The negative values in the figures presented in this section are ***benefits***. Positive values mean energy is consumed and/or emissions are produced. Negative values mean energy is generated and the emissions are prevented (also known as “offset”).

4.1 Energy

Scenarios 1 through 3, which include C&D recycling and wood combustion with energy recovery, have the greatest energy savings, with the energy savings of Scenario 3 being slightly greater since 100% coal is offset (Figure 4). A savings of over 7,000,000 MBTUs is equivalent to powering 191,000 homes for one year. The recycling impacts in Scenarios 4 and 5 create about half of the potential energy off-sets when the wood fraction is landfilled instead of combusted with energy recovery, but these two scenarios show the energy benefits to recycling. Landfilling of all the C&D debris consumes energy (scenarios 6 and 7) with the consumption 150,000 MBTU less when LFG-to-energy is implemented.

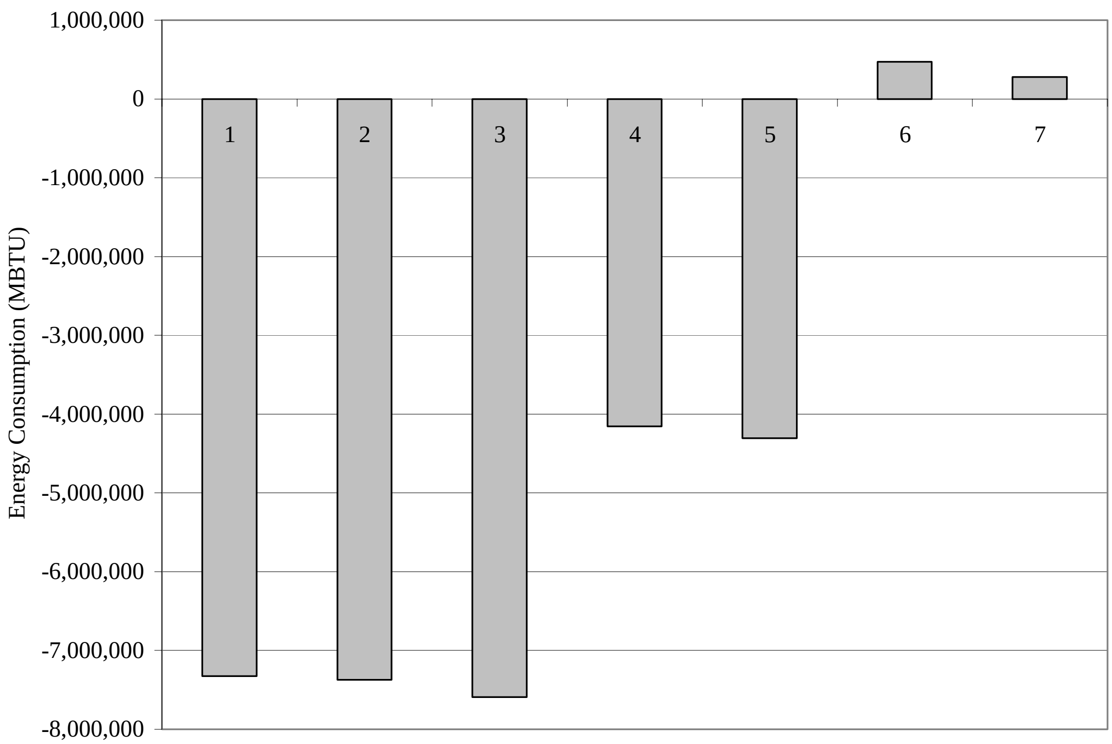

Figure 4. Energy Consumption (MBTU/yr)

4.2 Carbon Emissions

Scenarios 1, 2, and 3 which include recycling, and C&D wood combustion with energy recovery have the most carbon reductions by off-setting the NE power grid (Scenarios 1 and 2) and 100% coal (the highest offset, Scenario 3) (Figure 5). The reduction of 130,000 tons of carbon equivalents (scenario 3) is approximately equal to the annual carbon emissions from the electricity used by 55,000 households (using EPA's Greenhouse Gas Equivalency Calculator). The difference in transportation between Scenario 1 and 2 (115 miles) results in 1,000 tons difference of carbon equivalent emissions. Energy recovery from landfill gas in the 100% disposal scenario (Scenario 7) results in 2,500 tons less of carbon emissions than when the landfill gas is flared (Scenario 6).

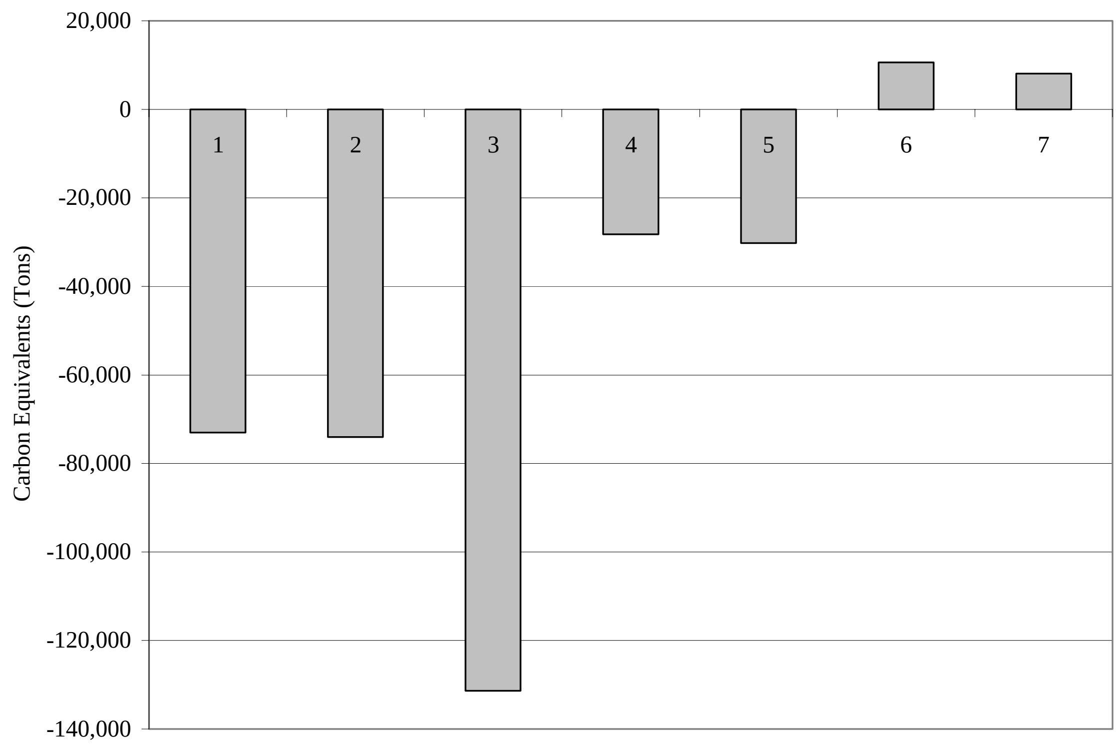

Figure 5. Total Carbon Equivalents in Air Emissions (Tons/yr)

4.3 Priority Air Pollutants

The greatest reduction of particulate matter (PM) is when material recovery occurs (all scenarios except 6 and 7) (Figure 6). Combustion of the wood with energy recovery provides some additional benefit through offsetting the NE power grid (Scenario 1 and 2); however a much larger benefit is shown when 100% coal is off-set (Scenario 3). The transportation difference between Scenarios 1 and 2 appears to be insignificant for PM. Although Scenarios 1 and 2 differ by 115 miles, this results in an increase of 9000 lb (4.5 tons) of PM, which is a small fraction (0.75%) of the overall quantity generated (1.2 million lbs or 600 tons). The difference between flaring and energy recovery for the landfill gas is negligible.

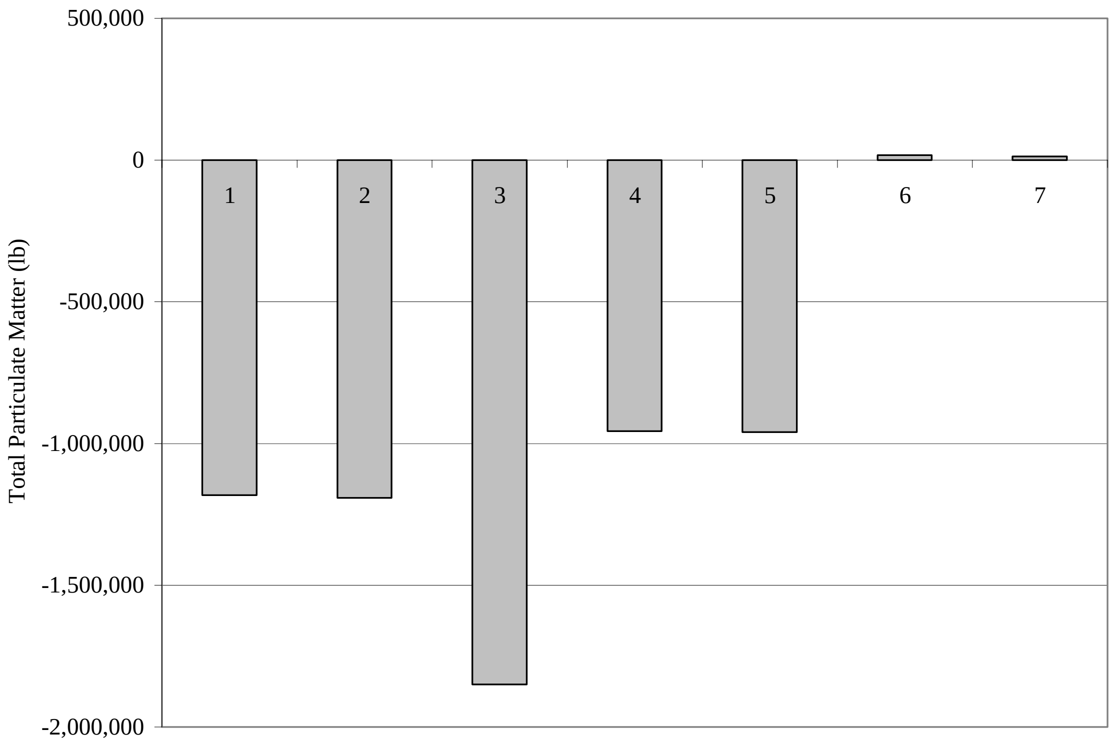

Figure 6. Total Particulate Matter in Air Emissions (lb/yr)

Recycling, along with C&D wood WTE with 100% coal offset (Scenario 3) provide the most benefits for reducing NOx emissions (Figure 7). Additionally, there is a 65,000 lb savings in NOx emissions from reducing the transport of the wood by 115 miles. There is also a significant increase (600,000 lbs) in NOx emissions when the C&D wood is landfilled after the rest of the materials are recycled.

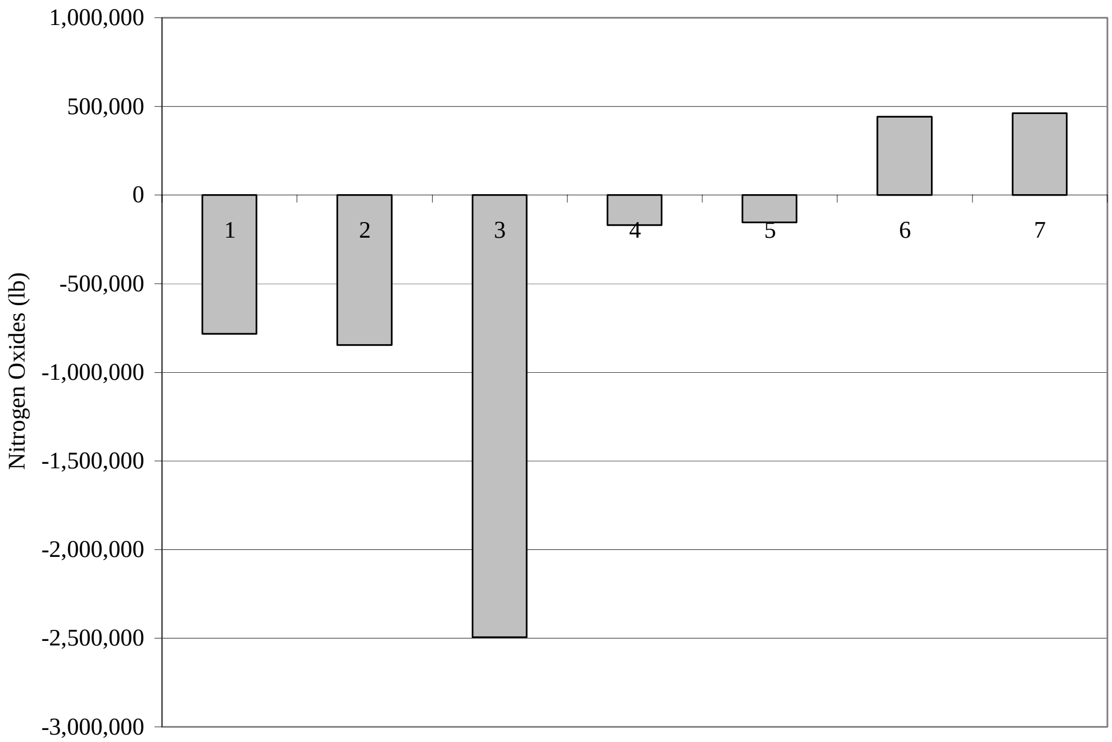

Figure 7. Total Nitrogen Oxides in Air Emissions (lb/yr)

For sulfur oxides, recycling and then combusting C&D wood with energy recovery provides the most benefits (Scenarios 1,2,3) with the 100% coal off-set providing the greatest reduction in emissions (Scenario 3) (Figure 8). The 115 mi transportation difference between Scenarios 1 and 2 results in an emission difference of 18,000 lb. Lastly, the difference between flaring landfill gas and energy recovery of landfill gas when all waste is disposed results in an off-set for energy production, but a relatively small difference (150,000 lb) between the scenarios.

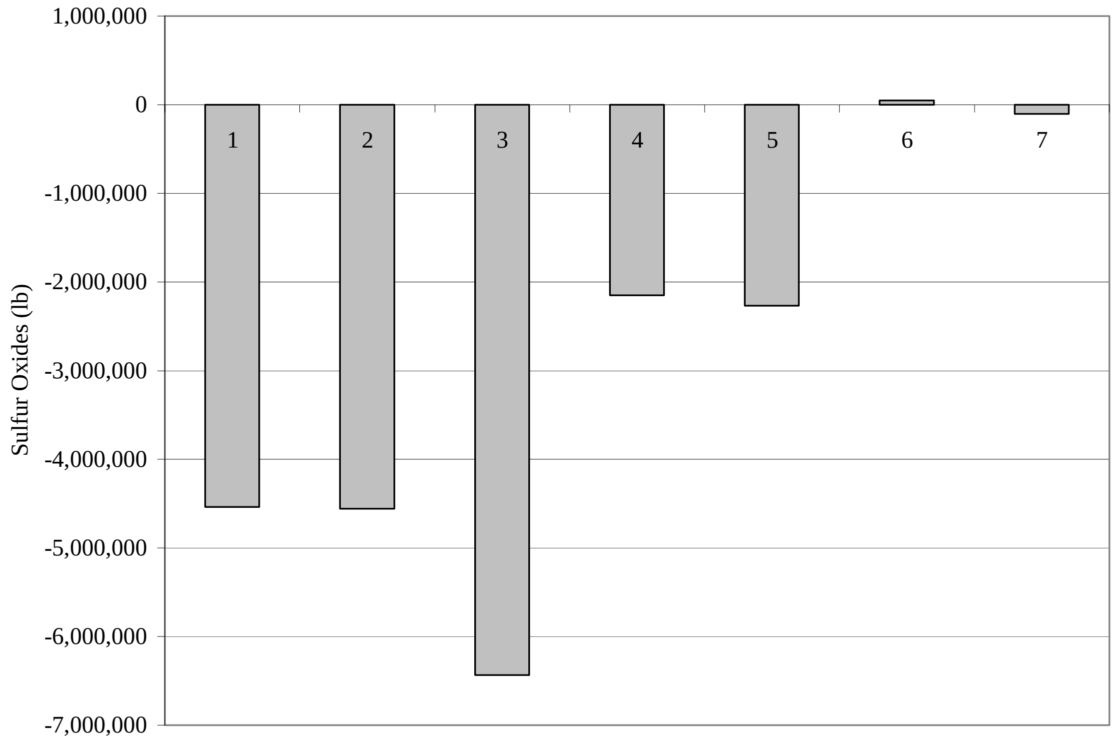

Figure 8. Total Sulfur Oxides in Air Emissions (lb/yr)

The recycling component of the scenarios (Scenarios 1 through 4) has the biggest reduction (1.8 million lbs) in emissions when compared to landfilling all the material (Scenarios 6 and 7) (Figure 9). The transportation difference (115 miles) results in a 63,000 lb reduction for a local facility. The 100% coal offset is nearly equal to the reductions in carbon monoxide gained from the offset of the energy generators in the NE energy grid.

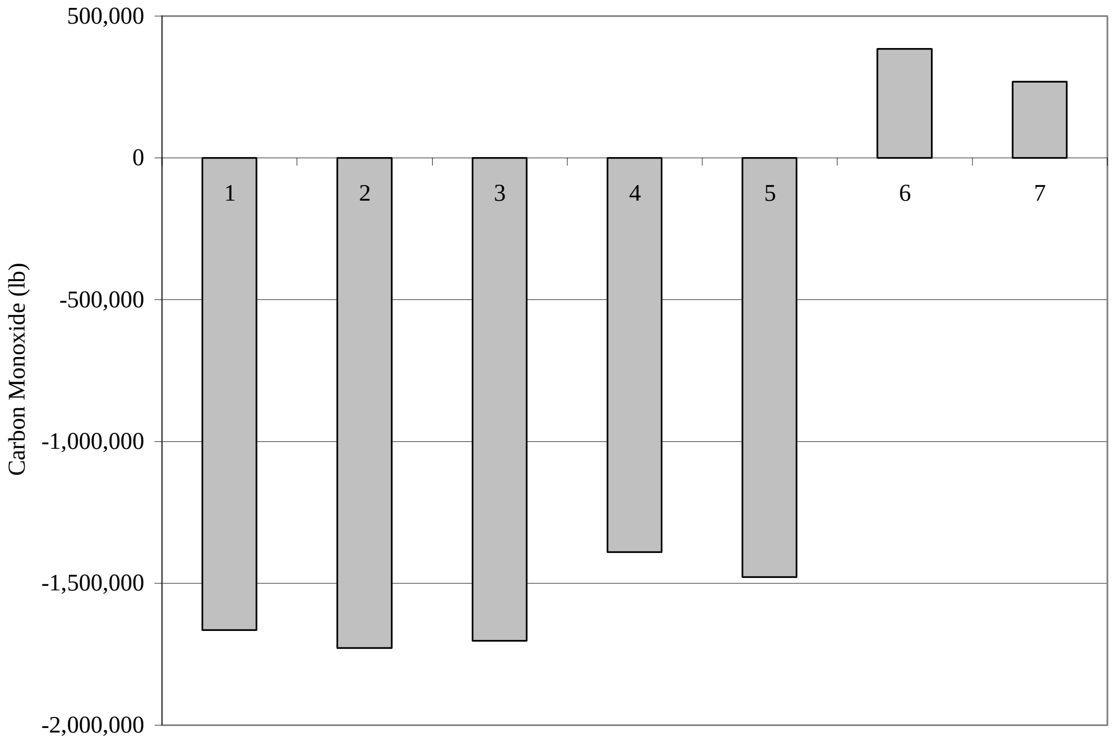

Figure 9. Total Carbon Monoxide in Air Emissions (lb/yr)

Lead emission reductions occur from -11 to -16 lb/yr in the scenarios which include recycling and C&D wood combustion with energy recovery offsetting either the NE energy grid or coal (Figure 10). Smaller off-sets also occur with recycling only (1-2 lb/yr) and landfill gas to energy (~1 lb/yr).

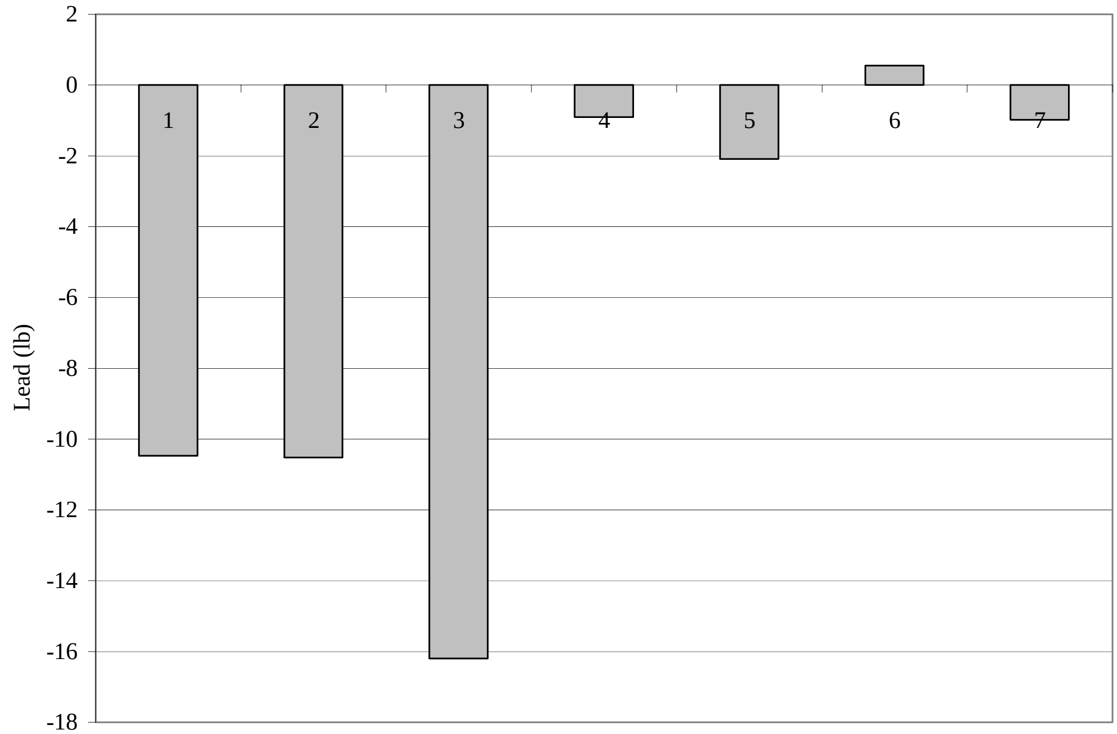

Figure 10. Total Lead in Air Emissions (lb/yr)

4.4 Other Air Emissions

For non-methane hydrocarbons, recycling has the most impact on reducing emissions (693,000 lb/yr reduction over landfilling alone), while scenarios 1 and 2, which include recycling and C&D wood combustion with energy recovery, provide the most total reductions (Figure 11). The savings associated with transporting the C&D wood locally for power production provides another 26,000 lbs/yr of emission savings, when comparing Scenario 2 versus Scenario 1.

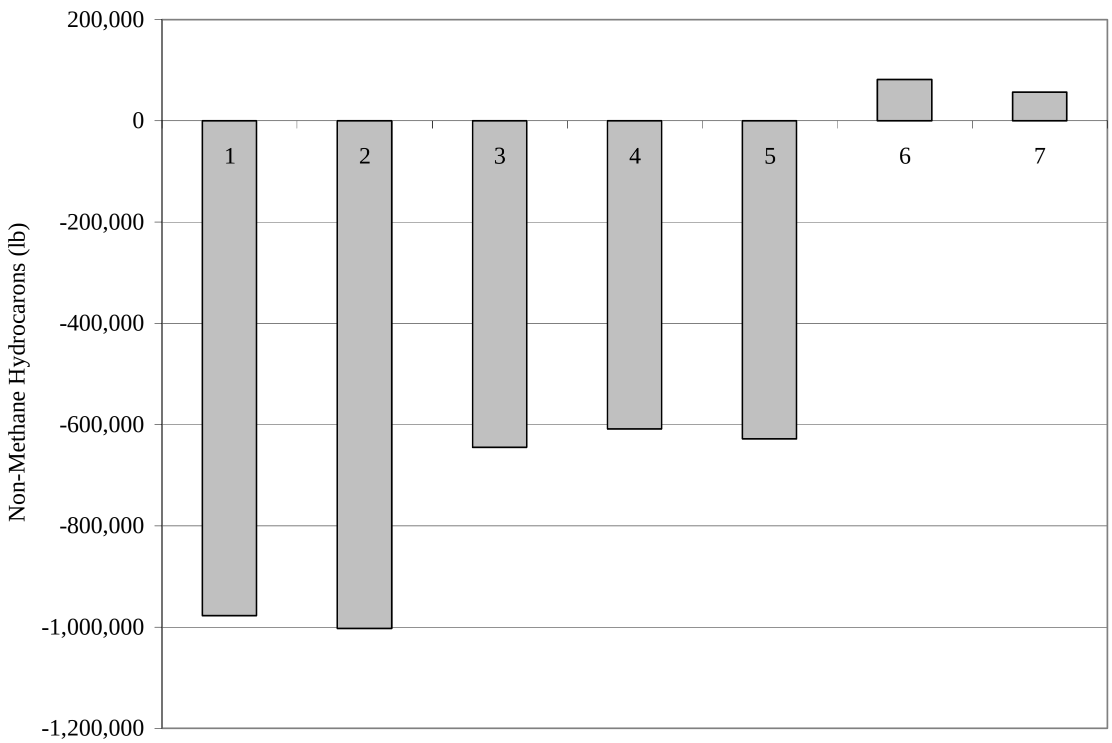

Figure 11. Total Non-Methane Hydrocarbons in Air Emissions (lb/yr)

The recovery and combustion of C&D wood for energy recovery is the most significant component in minimizing methane emissions. Scenarios 1 through 3 offset methane emissions with 100% coal offset from Scenario 3 being the greatest reduction (Figure 12). The difference (as it pertains to methane generation) in transportation to a local C&D wood-fired energy recovery facility is negligible (the difference between Scenario 1 and 2). All the scenarios without C&D wood combustion with energy recovery (Scenarios 4 through 7) emit methane.

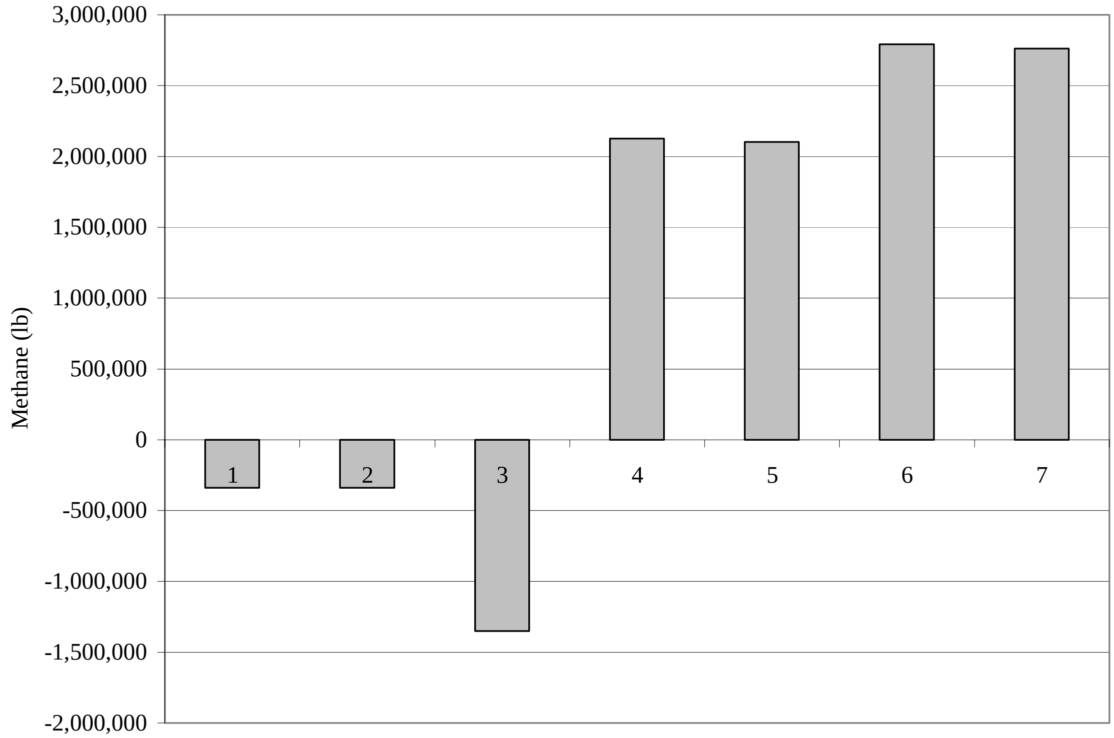

Figure 12. Total Methane in Air Emissions (lb/yr)

Scenarios 1 and 2 with C&D debris recycling, and combustion of wood with energy recovery offsetting the NE power grid allow for the greatest reductions of ammonia emissions (Figure 13). Off-setting 100% coal is similar to landfilling the C&D wood after leaving the recycling facility. There is no significant difference due to transportation differences (115 mile difference between Scenarios 1 and 2).

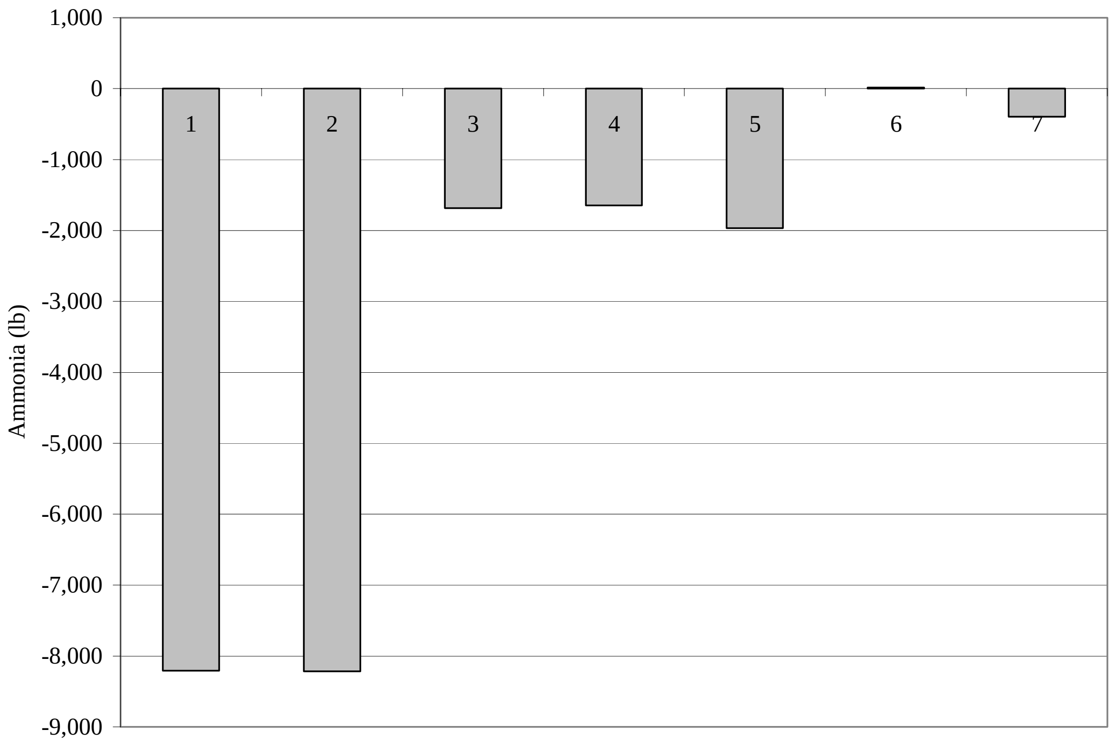

Figure 13. Total Ammonia in Air Emissions (lb/yr)

Scenario 3, with recycling C&D debris and combustion of the wood with energy recovery and offsetting 100% coal provides the greatest reduction of hydrochloric acid emissions (Figure 14). Recycling and wood combustion with energy recovery offsetting the NE energy grid, as well as recycling and landfilling wood are relatively similar in terms of reductions from 35,000 – 42,000 lb. Landfilling all of the C&D debris (Scenarios 6 and 7) does result in HCL emissions.

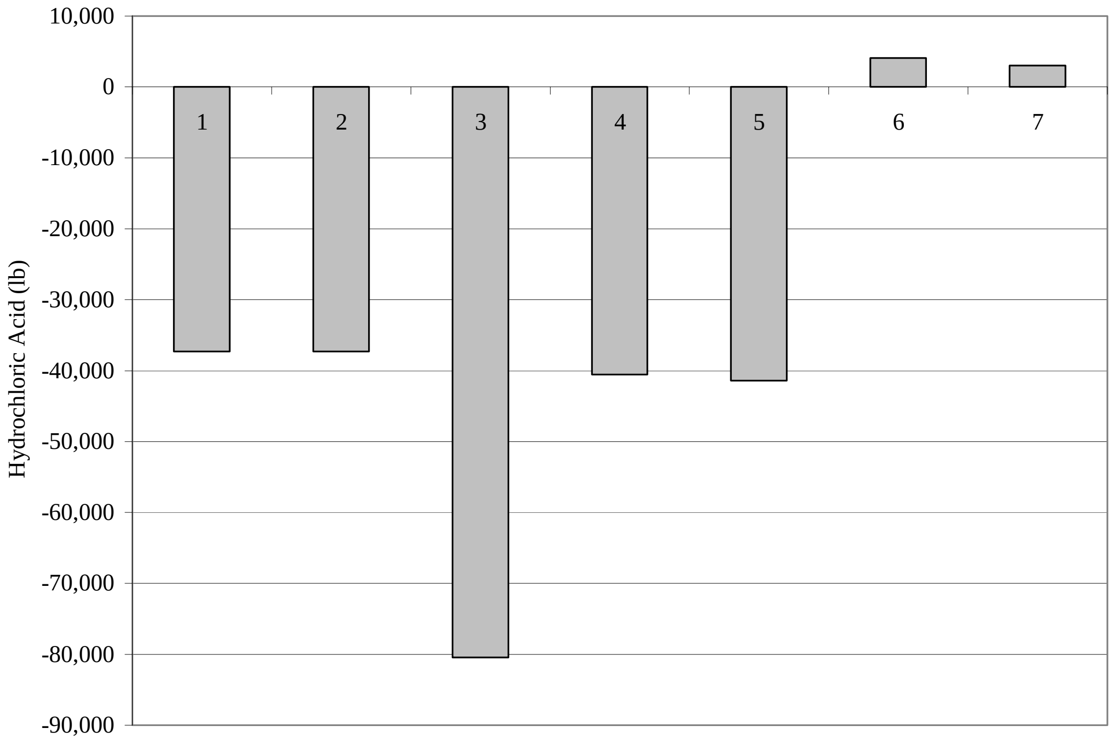

Figure 14. Total Hydrochloric Acid in Air Emissions (lb/yr)

4.5 Ancillary Solid Waste

The ancillary waste is an off-set for all scenarios except Scenario 6, which produces a small amount of waste through the management of C&D debris at the landfill (likely from landfill and/or landfill equipment construction). Examples of ancillary solid waste off-sets from materials recovery and energy production would be 1) when recycled materials are used instead of virgin materials, the waste produced from mining those virgin materials is avoided and 2) when a recovered material is used for energy instead of coal, for example, the waste produced from burning coal is avoided. Ancillary waste is the tonnage of C&D waste put through the model for the various C&D waste management scenarios as outlined in Table 4, but it is based upon this tonnage and how it is managed in each scenario (recycled, energy recovery, etc.). Scenario 3 provides the greatest offset since coal is displaced (Figure 15); this reflects the waste produced in the coal production and transportation industries. Scenarios 1, 2, 4 and 5 are relatively similar, although the combustion of wood with energy recovery reduces solid waste generation by 17,000 tons/yr over simply recycling alone (with wood being landfilled). The difference in transportation (115 miles) between Scenarios 1 and 2 is negligible.

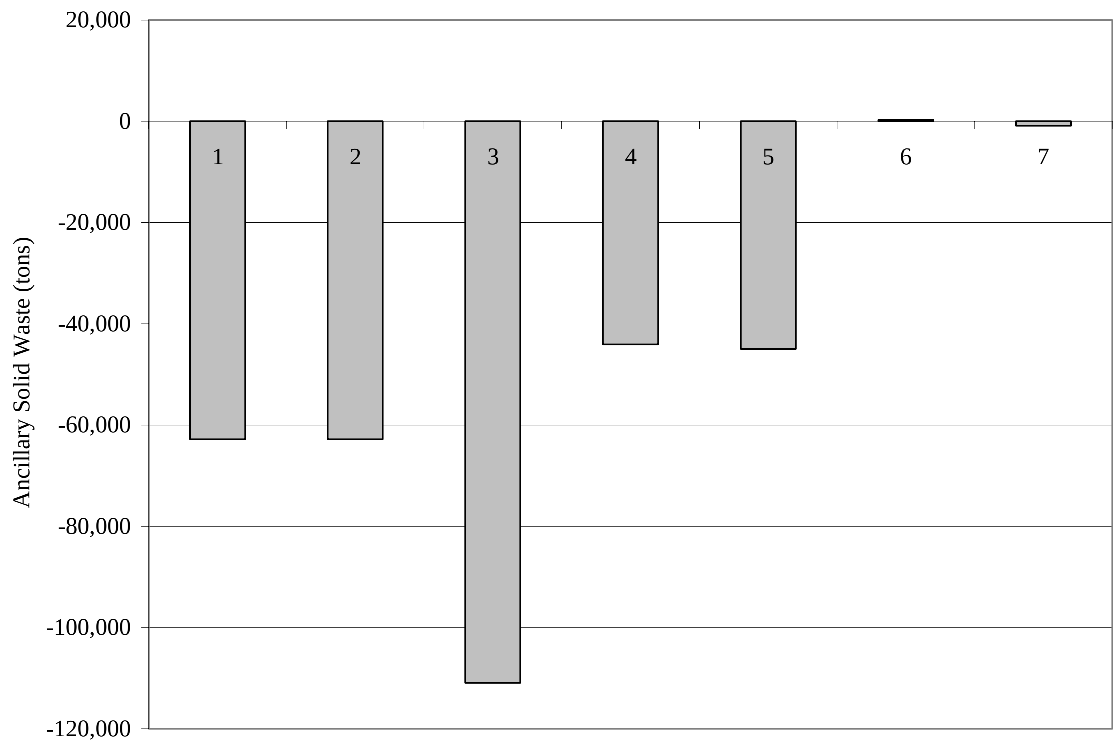

Figure 15. Total Ancillary Solid Waste (Tons/yr)

4.6 Water Emissions

Water emissions are based upon various components of C&D waste management. The negative values (avoidances), for example, can come from off-setting traditional energy sources (e.g., coal or oil) and the water emissions that are associated with those traditional energy sources from either the mining, transportation, combustion, or management of waste related to their use.

Scenario 2, recycling C&D, and combusting the wood with energy recovery, has the greatest benefits (Figure 16). Transportation has a relatively large impact on total dissolved solids (TDS) emissions since scenario 1, where transport is 115 miles more, has benefits reduced by 1 million lbs/yr. Recycling also has benefits (-1 million lbs/yr), with disposal of C&D having negative impacts (releases of TDS).

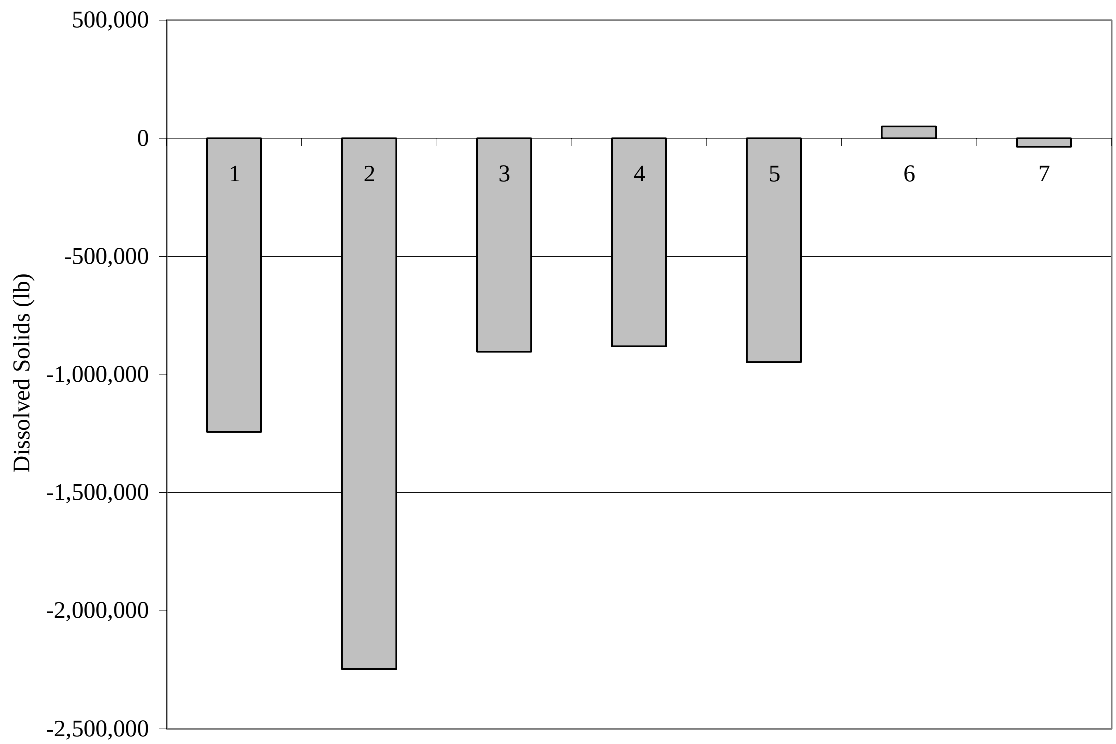

Figure 16. Total Dissolved Solids in Water Emissions (lb/yr)

Scenario 3, recycling C&D with combustion of the wood fraction off-setting 100% coal, has the greatest benefits in reduction of total suspended solids (TSS) emissions (Figure 17). Coal offset is most significant in reducing TSS. Increased transport between Scenario 1 and 2 and loss of recycling component increases TSS by approximately 100,000 lbs/yr.

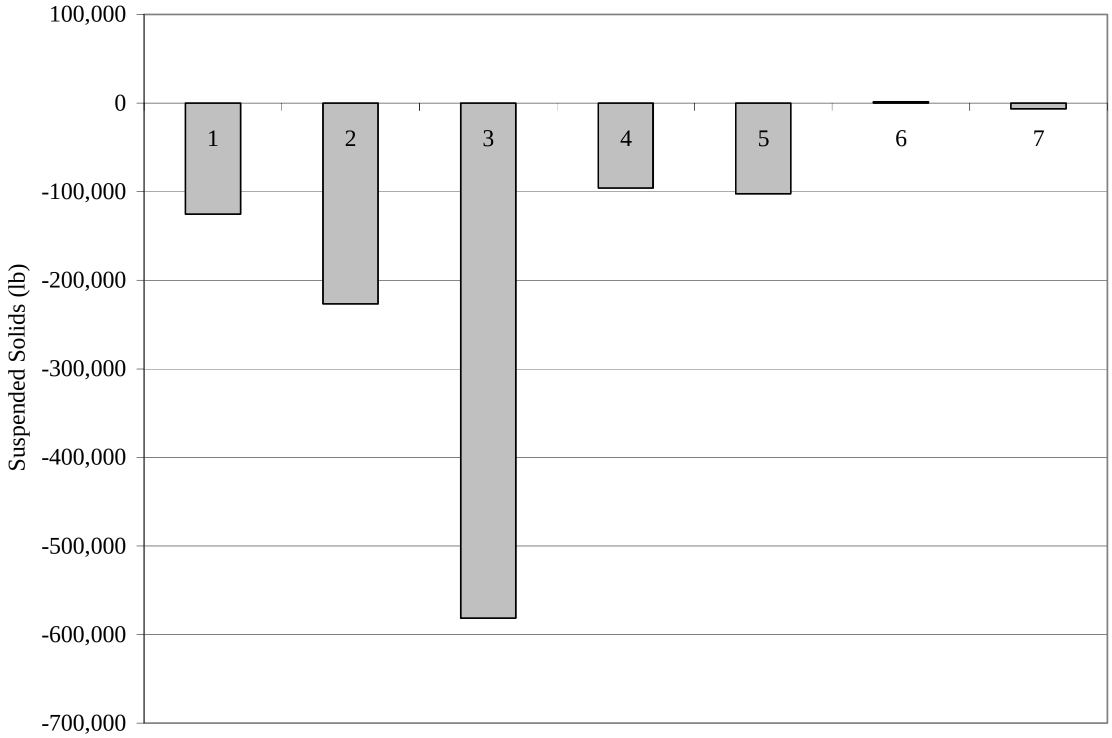

Figure 17. Total Suspended Solids in Water Emissions (lb/yr)

All of the waste management scenarios examined have impacts from biological oxygen demand (BOD) (Figure 18). Loss of the combustion of wood with energy recovery component has the greatest impact of increasing BOD. The differences between the coal offset, as well as transportation are negligible.

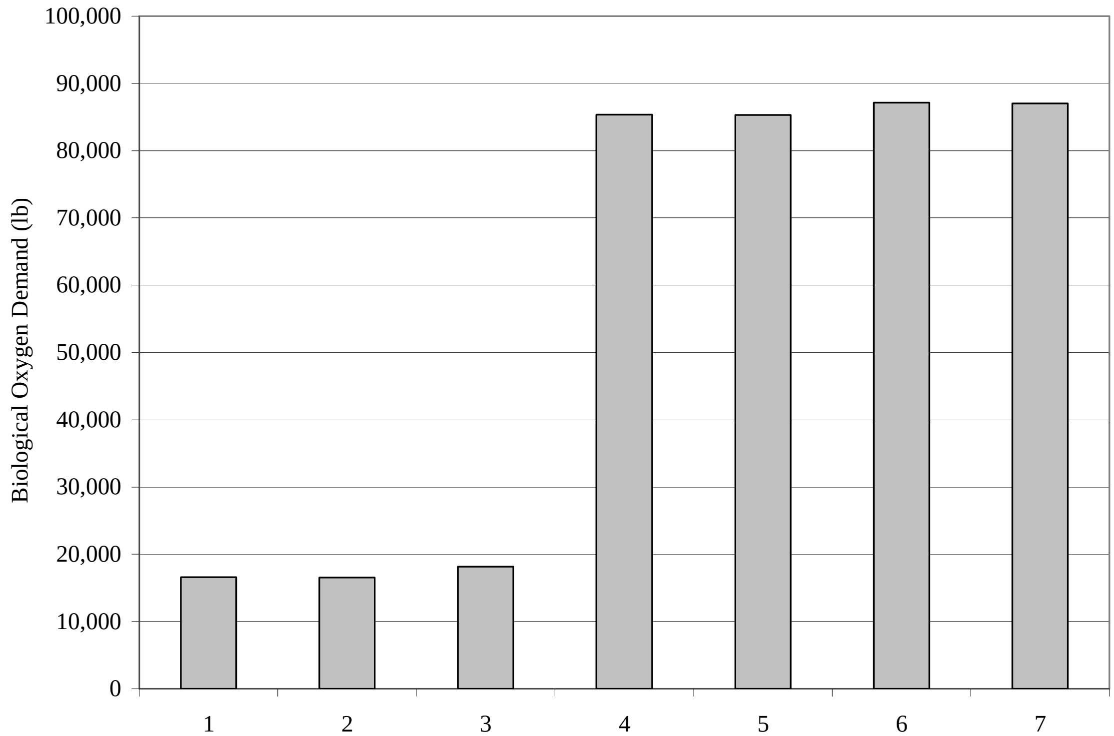

Figure 18. Total Biological Oxygen Demand in Water Emissions (lb/yr)

Scenarios 1, 2 and 3, which include C&D recycling, as well as combustion of the wood fraction with energy recovery result in benefits (reductions) in chemical oxygen demand (COD) (Figure 19). The recycling component is significant in minimizing COD, although impacts (positive values) are still realized. There is not a large difference between the two 100% disposal scenarios, which both have the greatest impacts of all the scenarios (Scenarios 6 and 7).

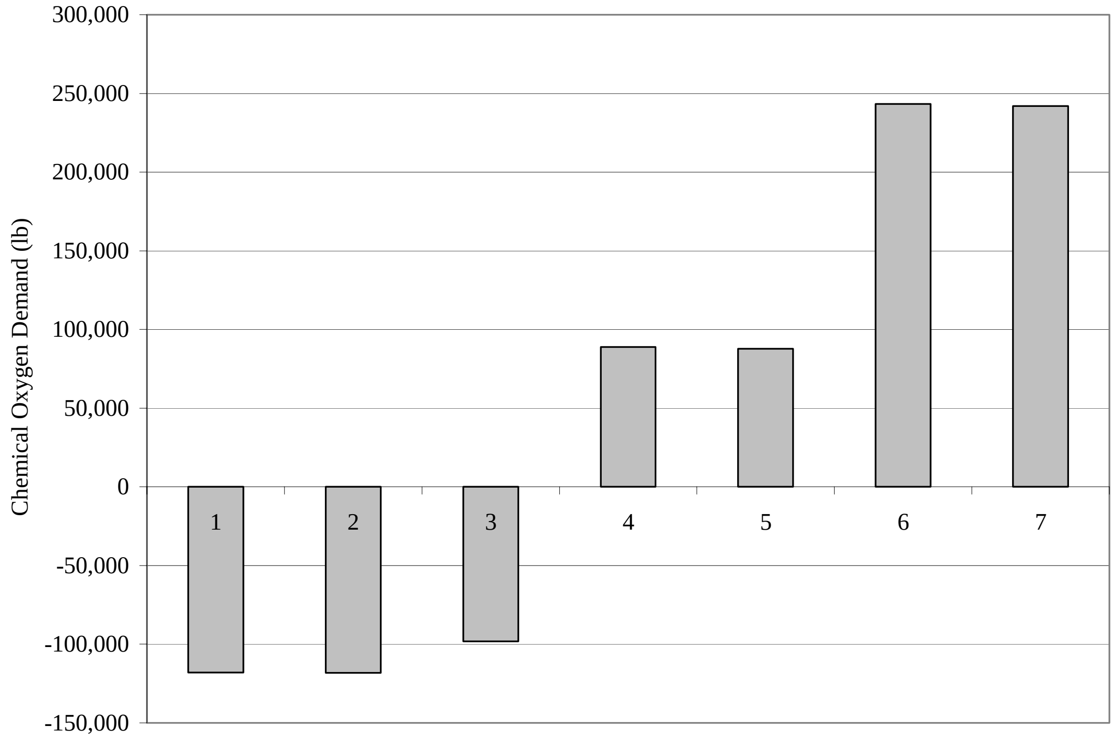

Figure 19. Total Chemical Oxygen Demand in Water Emissions (lb/yr)

Scenarios 1 and 2, which encompass C&D recycling and combustion of the wood component with energy recovery result in benefits (reductions) in oil emissions (Figure 20). Scenario 3, which is the same as Scenarios 1 and 2, but off-sets 100% coal results in an emission of less than 10,000 lbs/yr of oil, which is the third lowest scenario. While the recycling only scenarios have impacts (positive results), they are significantly less (60,000 lbs/yr less) than that of the 100% disposal scenarios (Scenarios 6 and 7).

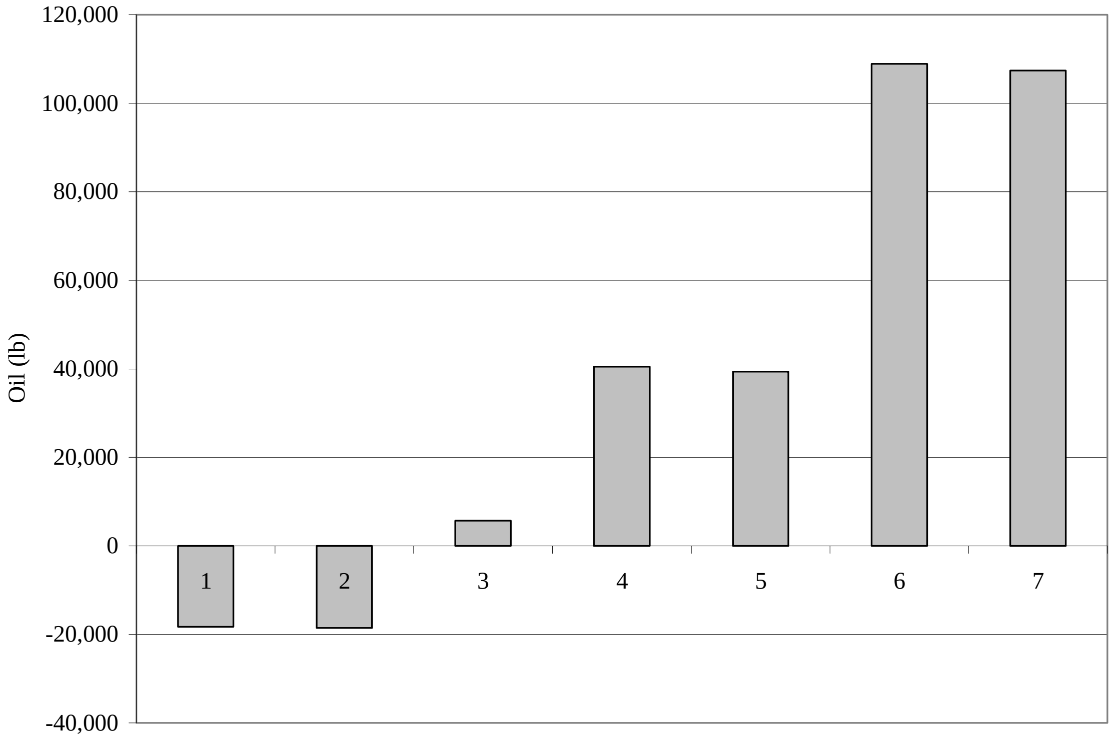

Figure 20. Total Oil in Water Emissions (lb/yr)

Scenario 3, recycling of C&D wood with combustion of the wood fraction and energy recovery with 100% coal off-set, results in the greatest benefits (reduction) of sulfuric acid generation (Figure 21). There are also quantifiable reductions form Scenarios 1, 2 and 4. The 100% disposal scenarios have the lowest reductions.

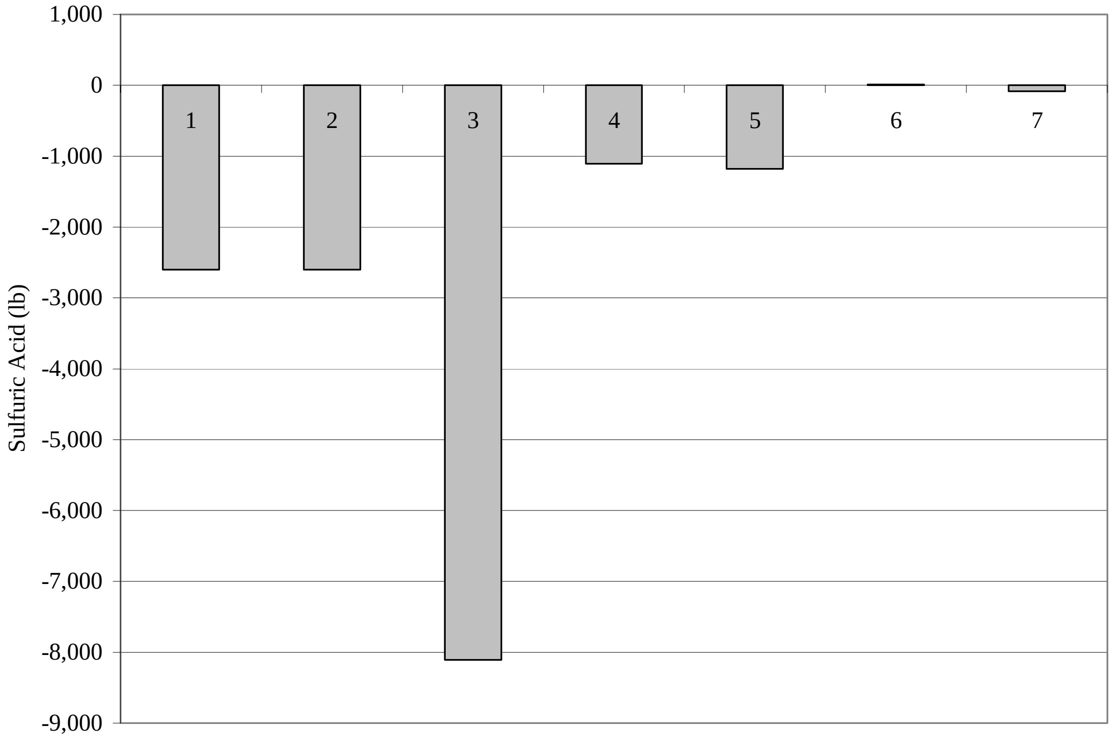

Figure 21. Total Sulfuric Acid in Water Emissions (lb/yr)

Scenario 3, recycling of C&D wood with combustion of the wood fraction and energy recovery with 100% coal off-set, results in the greatest benefits (reduction) of iron emissions in water (Figure 22). There are also quantifiable reductions form Scenarios 1, 2 and 4. The 100% disposal scenarios have the lowest reductions.

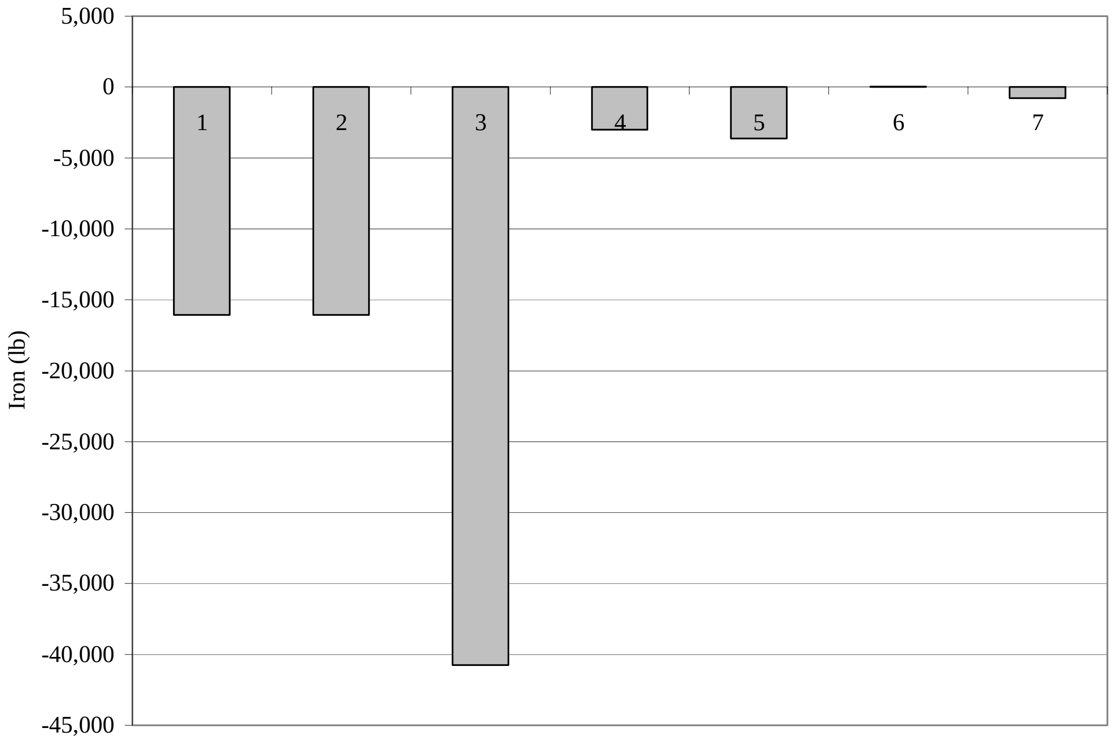

Figure 22. Total Iron in Water Emissions (lb/yr)

Scenarios 1, 2 and 3, which include C&D wood recycling and combustion of the wood fraction with energy recovery, result in benefits/reductions in ammonia releases (Figure 23). The recycling component is significant in minimizing ammonia, although impacts (positive values) are still realized (Scenarios 4 and 5). There is not a large difference between the two 100% disposal scenarios, which both have the greatest impacts of all the scenarios (Scenarios 6 and 7).

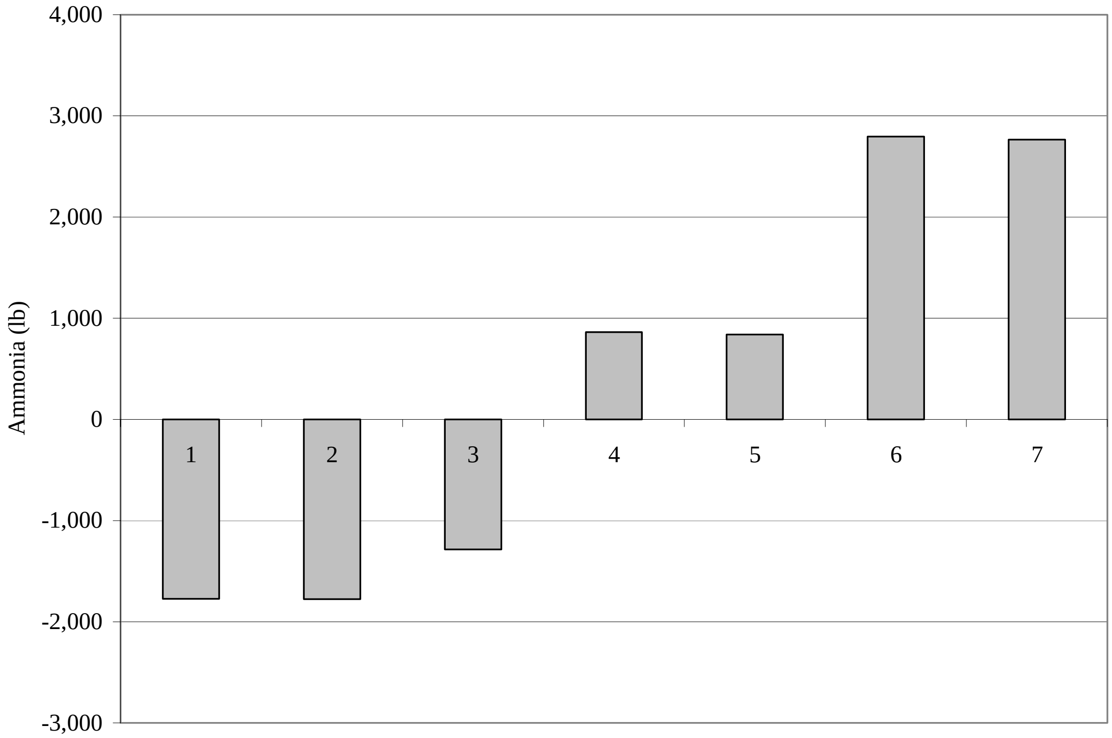

Figure 23. Total Ammonia in Water Emissions (lb/yr)

Copper emissions from all scenarios are negligible at less than 1.3E-6 lb/yr.

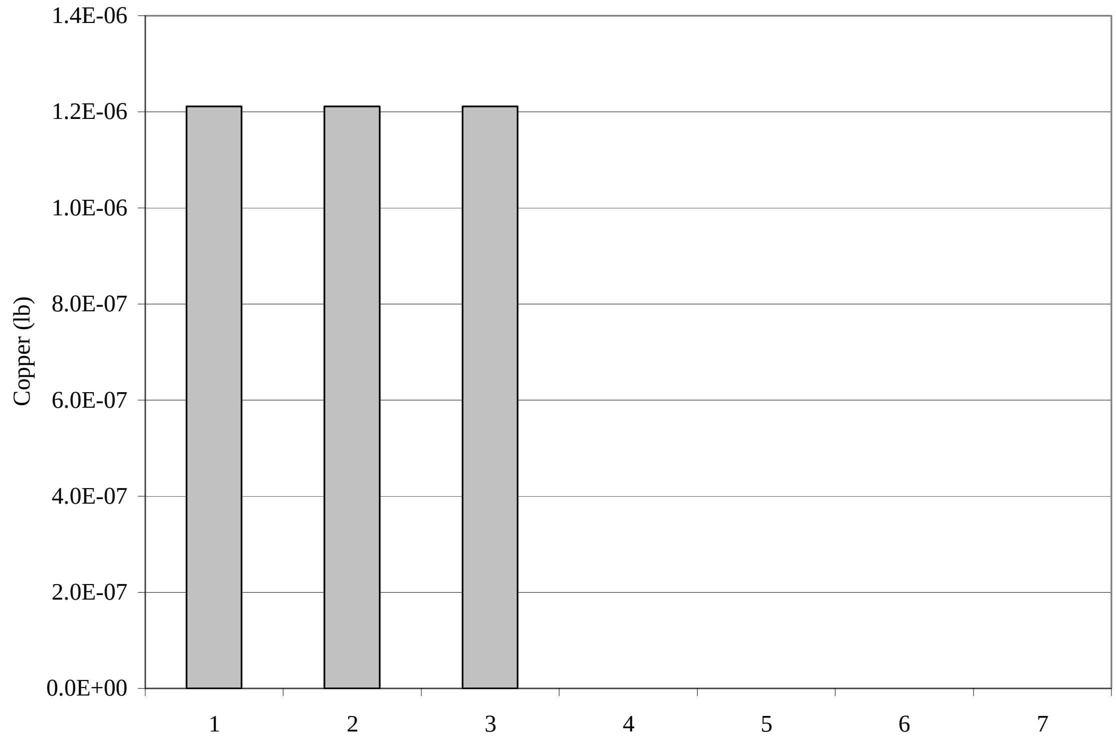

Figure 24. Total Copper in Water Emissions (lb/yr)

Scenarios 1 and 2, with C&D wood debris recycling and combustion of wood with energy recovery offsetting the NE power grid, allow for the greatest reductions of cadmium in water emissions (Figure 25). Off-setting 100% coal (Scenario 3) is similar to landfilling the C&D wood after leaving the recycling facility (recycling only) (Scenarios 4 and 5). There is no significant difference when transporting the 115 mile difference between Scenarios 1 and 2.

The 100% disposal scenarios (Scenarios 6 and 7) result in an emission of cadmium for the flare scenario (Scenario 6) and the lowest benefit/reduction for Scenario 7 (gas-to-energy).

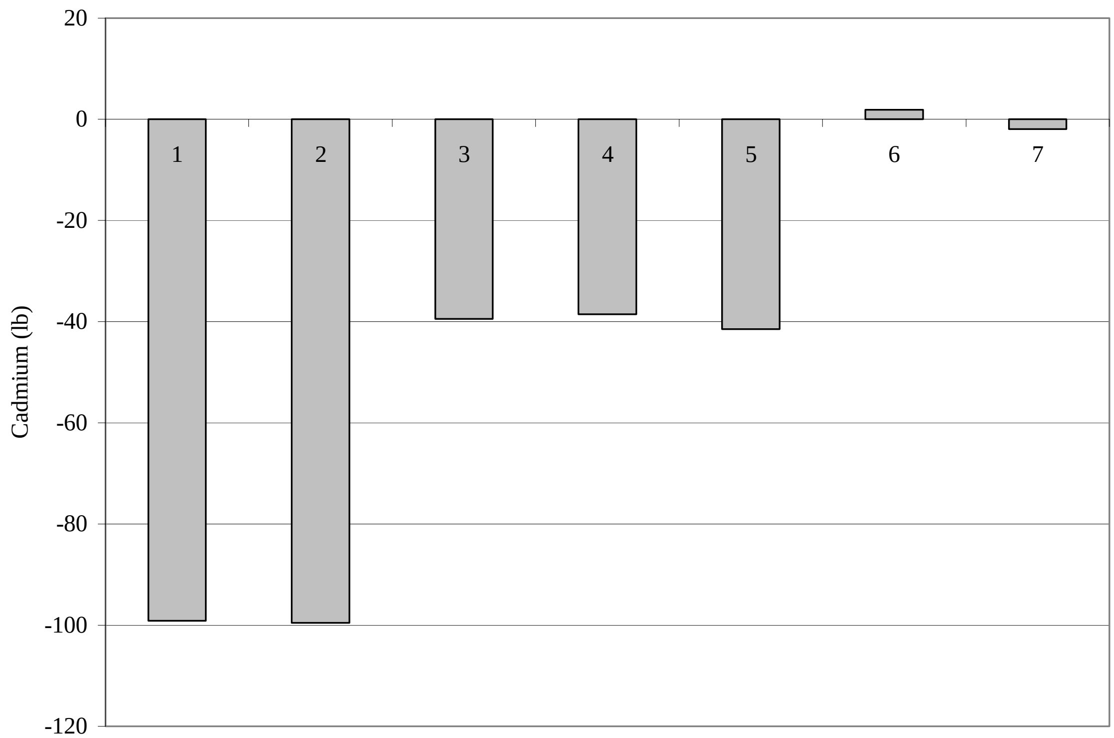

Figure 25. Total Cadmium in Water Emissions (lb/yr)

Although each scenario has a release of arsenic impact, releases of arsenic in water for all seven waste management scenarios are very low (less than 0.06 lb/yr) (Figure 26). However, all three scenarios that include recycling and combustion of the C&D wood with energy recovery provide the greatest reduction in emissions. The arsenic emissions from the recycling only scenarios (4 and 5) and the scenarios disposing of 100% of the debris (scenarios 6 and 7) are similar.

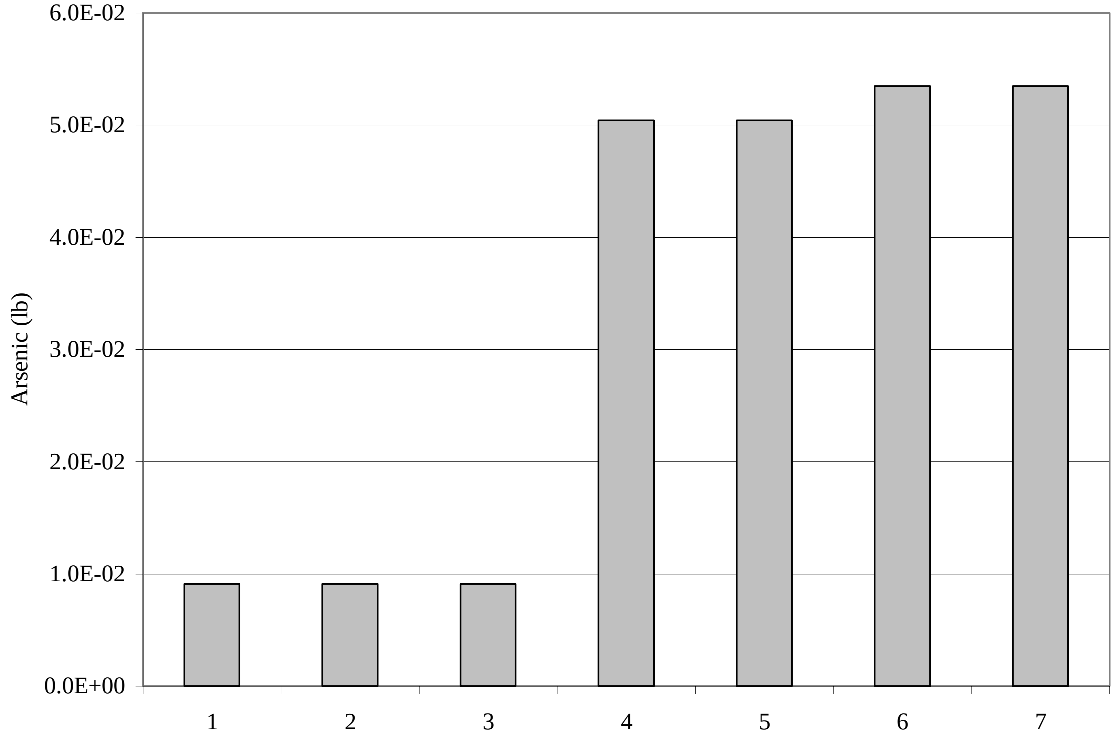

Figure 26. Total Arsenic in Water Emissions (lb/yr)

The mercury emissions as well as reductions are again very low (less than 0.06 lbs/yr) (Figure 27). However, Scenarios 1 through 5 result in similar off-sets/reductions of mercury, while the 100% disposal scenarios (6 and 7) result in a very small amount (less than 0.01 lb/yr) of mercury emissions. There is a small increase (less than 0.01 lb/yr) of mercury emissions to benefits from the combustion of wood with energy recovery while off-setting the NE power grid (Scenarios 1 and 2 versus Scenario 3, 4 and 5).

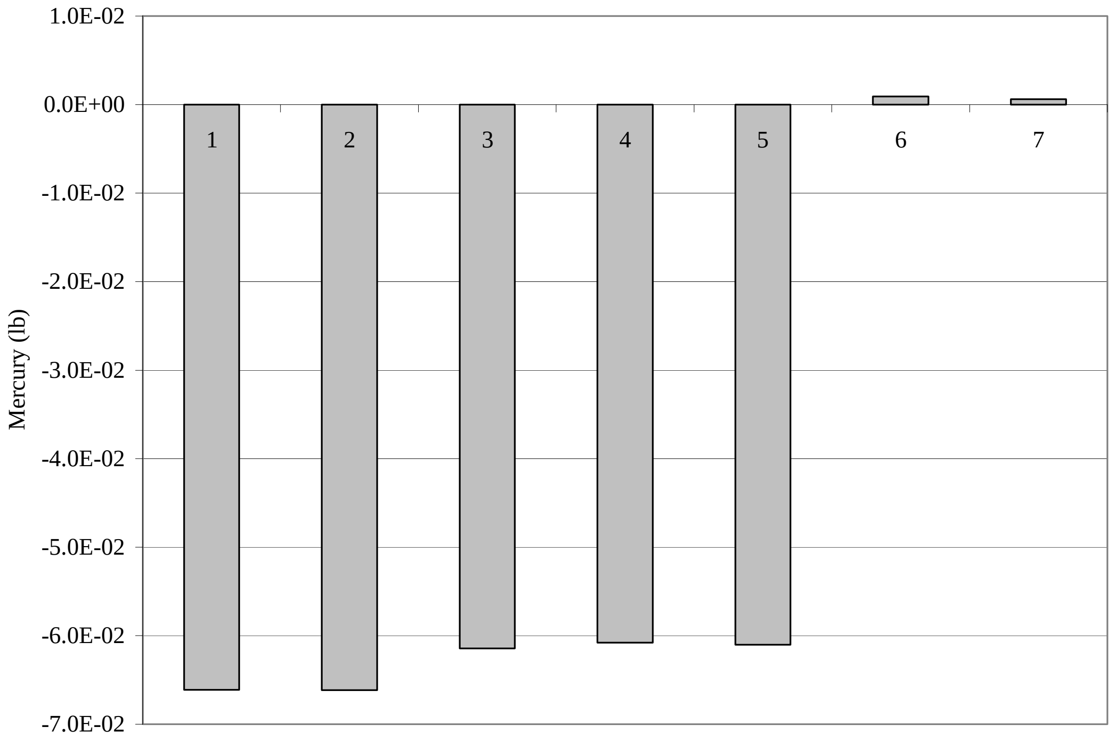

Figure 27. Total Mercury in Water Emissions (lb/yr)

Scenarios 1 through 5 result in similar off-sets/reductions of total phosphate emissions in water, while the 100% disposal scenarios (6 and 7) result in no benefits (Figure 28). Recycling seems to be the only component that positively affects phosphate releases in water.

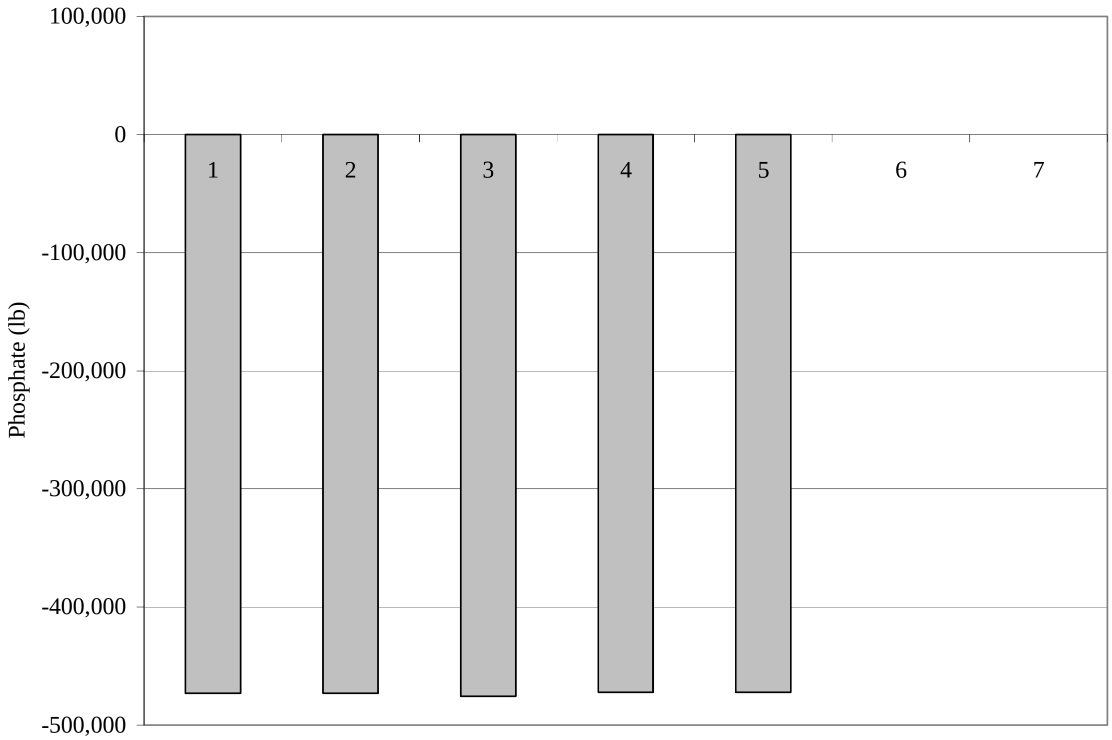

Figure 28. Total Phosphate in Water Emissions (lb/yr)

Although each scenario has a release of selenium in water, releases for all seven waste management scenarios are very low (less than 0.018 lb/yr) (Figure 29). However, all three scenarios that include recycling and combustion of the wood with energy recovery (Scenarios 1, 2 and 3) provide the lowest selenium emissions. The emissions of recycling only (Scenarios 4 and 5) and disposing of 100% of the debris (Scenarios 6 and 7) are similar.

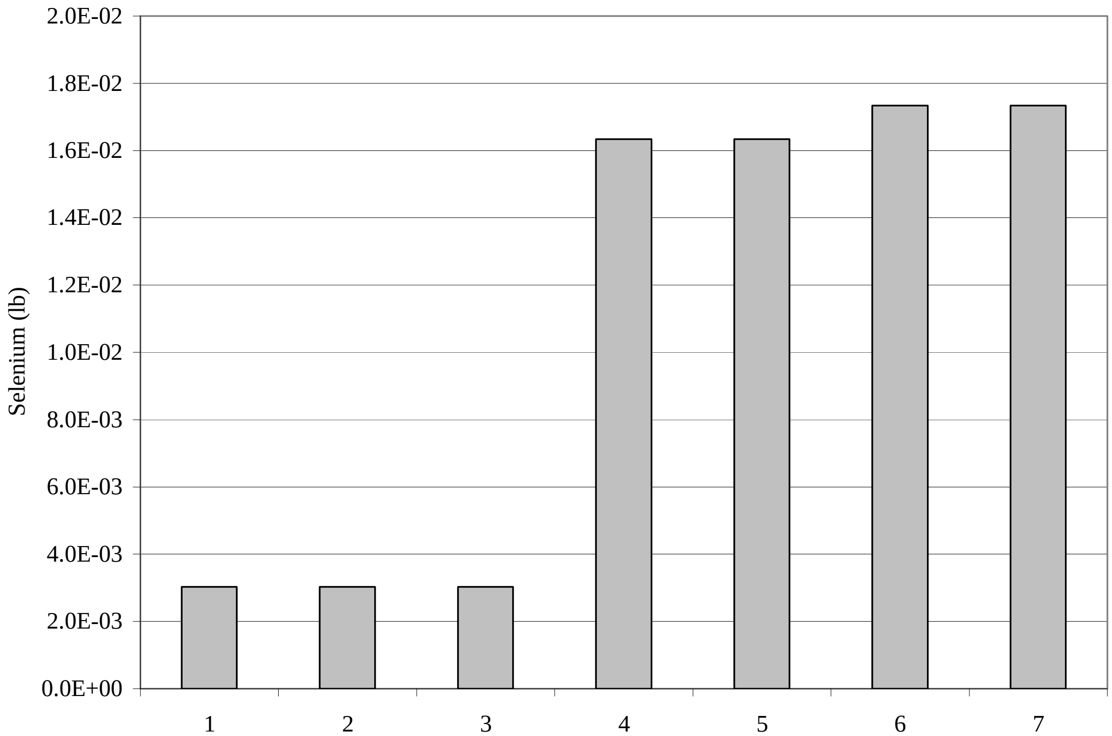

Figure 29. Total Selenium in Water Emissions (lb/yr)

Scenarios 1 and 2, recycling of C&D with combustion of the wood with energy recovery and off-setting the NE power grid, result in the greatest reduction in chromium emissions in water (Figure 30). The similar scenario with the 100% coal off-set (Scenario 3) is nearly equal to the scenarios with recycling only and disposal of the wood (Scenarios 4 and 5). The 100% disposal scenarios (6 and 7) result in chromium emissions for the flare of landfill gas scenario and a relatively small reduction/benefit to the landfill gas-to-energy scenario, respectively.

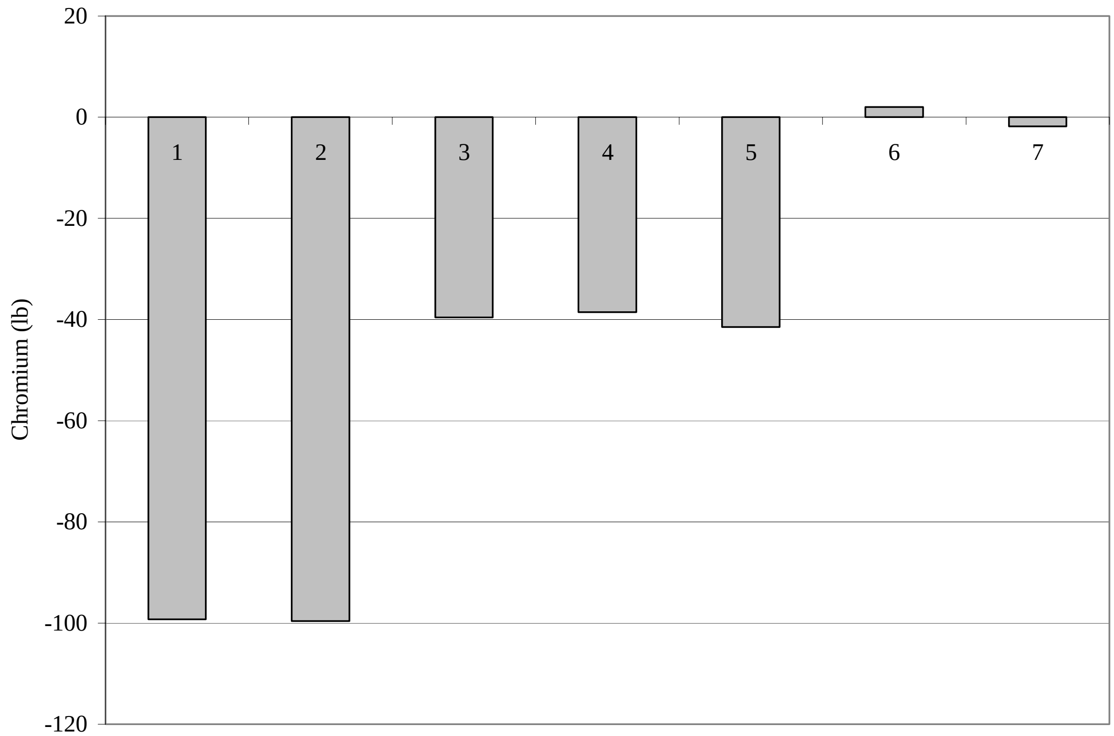

Figure 30. Total Chromium in Water Emissions (lb/yr)

Lead emissions in water benefits/reductions and impacts are low (less than 0.25 lbs/yr for benefits and less than 0.05 lbs/yr for impacts). Scenarios 1 and 2, recycling of C&D with combustion of the wood with energy recovery and off-setting the NE power grid, result in the greatest reduction in lead emissions in water (Figure 31). The similar scenario with the 100% coal off-set (Scenario 3) has slightly greater benefits than the scenarios with recycling only and disposal of the wood (Scenarios 4 and 5). The 100% disposal scenarios (6 and 7) result in net lead emissions to water for both.

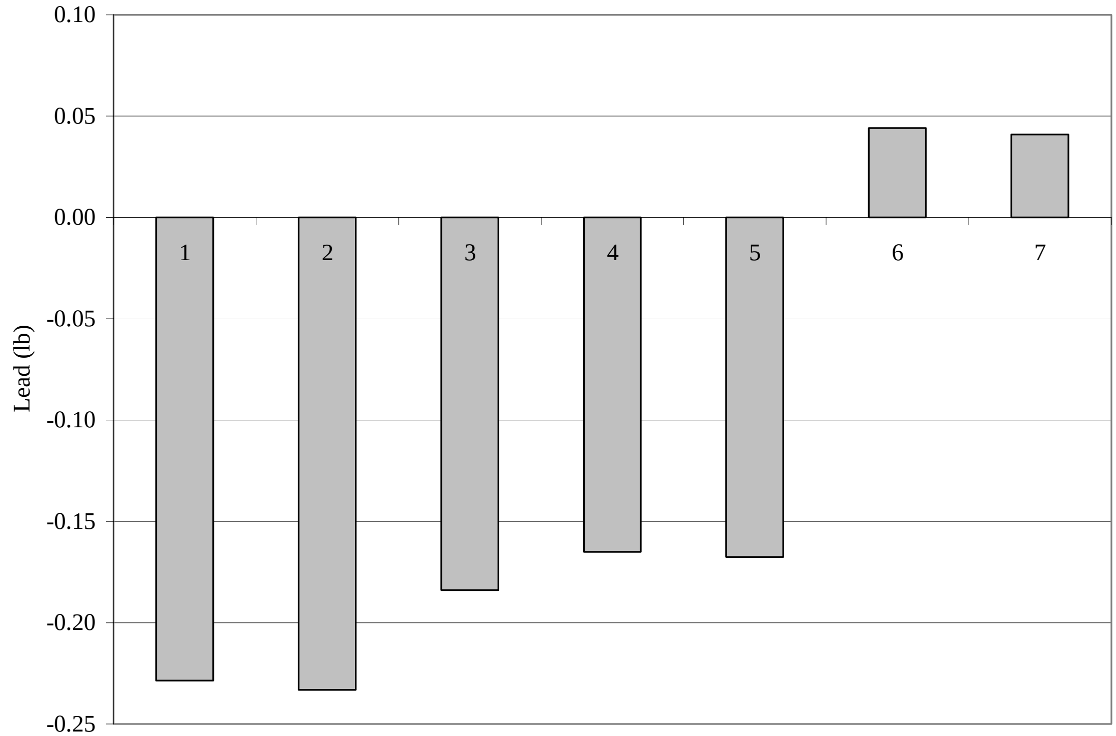

Figure 31. Total Lead in Water Emissions (lb/yr)

Scenarios 1 through 5 result in similar off-sets/reductions of total zinc in water, while the 100% disposal scenarios (6 and 7) result in no benefits (Figure 32). Recycling seems to be the only component that positively affects zinc releases in water.

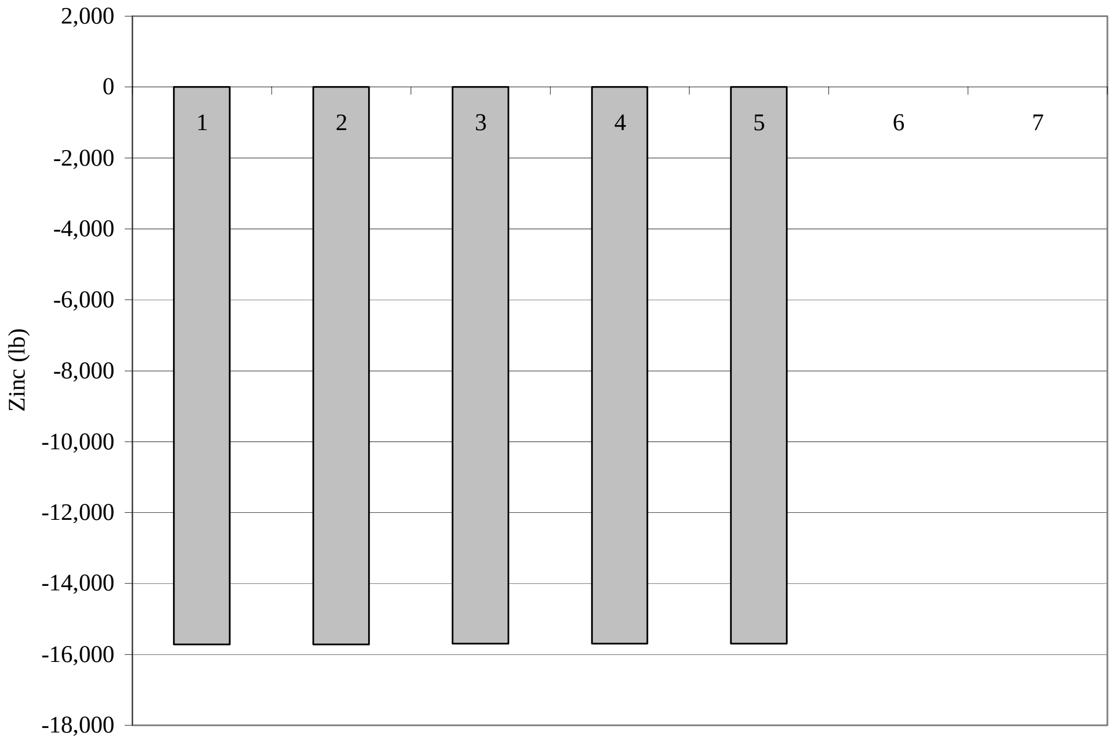

Figure 32. Total Zinc in Water Emissions (lb/yr)

4.7 Results Ranking (Outranking)

As detailed in the sections above, recycling followed by combustion of wood with energy recovery and offsetting either the NE energy grid or coal result in a multitude of benefits and offsets. In order to determine which scenarios ranked highest more frequently, the data was ordered from lowest to greatest for each parameter using an outranking procedure. The alternative with the lowest emission (or greatest benefit) received a score of 1, the next lowest emission or greatest benefit a 2, etc. In this way, each alternative is compared based upon its relative ranking for each parameter (each environmental impact parameter is weighted equally). This simple methodology does not account for different contaminants having different toxicity potentials for both humans and the ecology as there is no current consensus as to how to rank these impacts. The outranking results (average ranking for each scenario) is presented in Table 5; note, the *lower* the Average Impact Ranking, the *less* impact the scenario makes.

Table 5. Summary Scenario Rankings and Impact Score

Scenario Ranking	Average Impact Ranking
Scenario 2	1.7
Scenario 1	2.6
Scenario 3	2.6
Scenario 5	3.9
Scenario 4	4.6
Scenario 7	5.8
Scenario 6	6.7

Table 5 shows that Scenario 2 (C&D recycling with local combustion of wood with energy recovery offsetting the NE energy grid) had the lowest impact ranking, followed by Scenarios 1 and 3, which are tied for the second lowest average impact ranking. All of the C&D recycling-only scenarios resulted in less overall impact than the disposal-only scenarios. For the disposal scenarios, the landfill gas-to-energy scenario has more offsets than the flared landfill gas.

This ranking indicates which scenario provided the lowest impacts most frequently, and it is clear from the results that C&D recycling facilities provide many environmental benefits to the state of New Hampshire and the ultimate end-use of C&D wood for energy recovery has additional benefits.

The benefits afforded by C&D recycling and use of the recovered wood fraction for energy production have significant ramifications. For example, recycling C&D debris and use of C&D wood in energy recovery facilities produces a net gain in energy production of over 7,000,000 MBTU/yr – enough to power 191,000 homes in New Hampshire (according to the US Census Bureau this is approximately 1/3 of all housing units in NH in 2005). Similarly, 70,000 to 130,000 tons/yr of carbon emissions are eliminated; 130,000 tons/yr of carbon equivalent emissions are approximately equal to the annual carbon emissions from the electricity used by 55,000 households (using EPA's Greenhouse Gas Equivalency Calculator). Criteria air pollutants are significantly reduced as well when combusting C&D wood with energy recovery producing:

- 600 tons/yr less particulate matter,
- 430 tons/yr less of nitrogen oxides,
- 2,300 tons/yr less of sulfur oxides,
- 890 tons/yr less of carbon monoxide,
- and 10 lbs less lead (with NE energy grid offset) when compared to landfilling.

Most of the off-sets outlined in this section come from the fact that the C&D wood is an available source of energy and it can offset traditional energy sources when it is used for energy production. The use of alterative energy sources will continue to increase and this analysis illustrates that C&D wood waste, readily available in the solid waste stream, can contribute to an integrated alternative energy portfolio.

4.8 Virgin Wood Scenario Comparison

In order to compare the combustion of C&D wood product and the virgin wood currently being combusted, the MST DST modeled the combustion of virgin wood harvested in northern New Hampshire (at a distance of approximately 150 miles) in a combustion facility. The energy generated offsets the NE power grid (20% Coal, 12% Natural Gas, 14% Oil, 37-38% Nuclear, 16% Hydroelectric and .04% wood) and the ash is used for some beneficial use application (not landfilled). In this case the tonnage put through the model is 280,000 tons, equal to the amount of C&D wood generated annually in NH. This scenario was compared to the same quantity of C&D wood combusted with energy recovery at a local facility (25 miles away) and offsetting the NE power grid with the ash from the combustion facility being landfilled.

While combustion of virgin wood and C&D wood both produce energy, the C&D wood combustion produces over 1.2 million MBTU/yr more energy (50% more) for the same amount of wood (280,000 tons) when compared to virgin wood combustion because of the high water content of virgin wood (45% moisture/4500 BTU/lb for virgin wood versus 12% moisture/7380 BTU/lb for C&D wood) (Figure 33). This is enough extra energy to power over 33,000 homes for one year. Additionally the carbon offsets are higher for C&D wood – by 16,700 tons of carbon equivalents (using EPA's Greenhouse Gas Equivalency Calculator, like taking 11,000 passenger cars off the road for 1 year) (Figure 34).

Based upon best available air pollution technologies and a wood quantity of 280,000tons/yr, the C&D wood used for energy production produces (Figures 35 and 36):

- 50 tons/yr less particulate matter,
- 200 tons/yr less of nitrogen oxides,
- 485 tons/yr less of sulfur oxides,
- 69 tons/yr less of carbon monoxide when compared to virgin wood.
- Additionally lead is reduced by 9 lb (~1.5 lb difference from virgin wood) with the NE energy grid offset.

The reason for the reduction in emissions for the combustion of C&D wood is because the BTU value per pound of C&D wood is greater. Therefore, more electricity from fossil fuels is off-set than electricity produced by virgin wood combustion. The more fossil fuel electricity off-set, the more emission off-sets are made. Consequently, even if there is ash to be landfilled or a slightly higher metal content in C&D wood, the greater electricity production creates larger benefits.

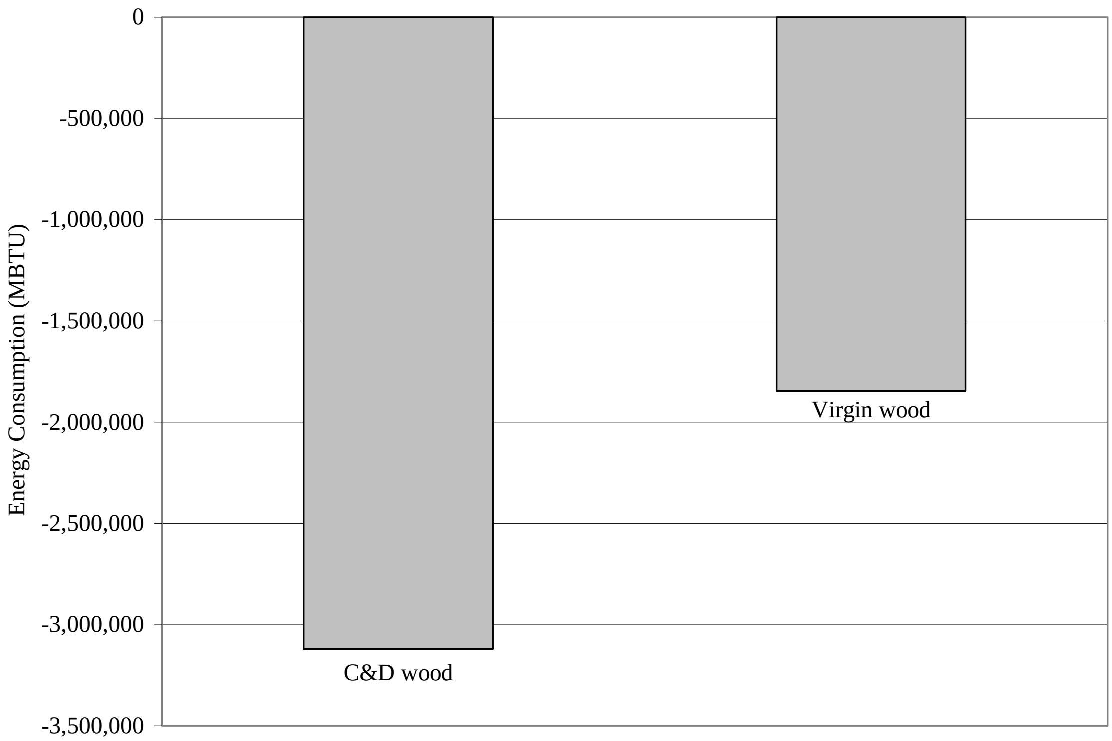

Figure 33. Energy Consumption C&D Wood versus Virgin Wood (MBTU/yr)

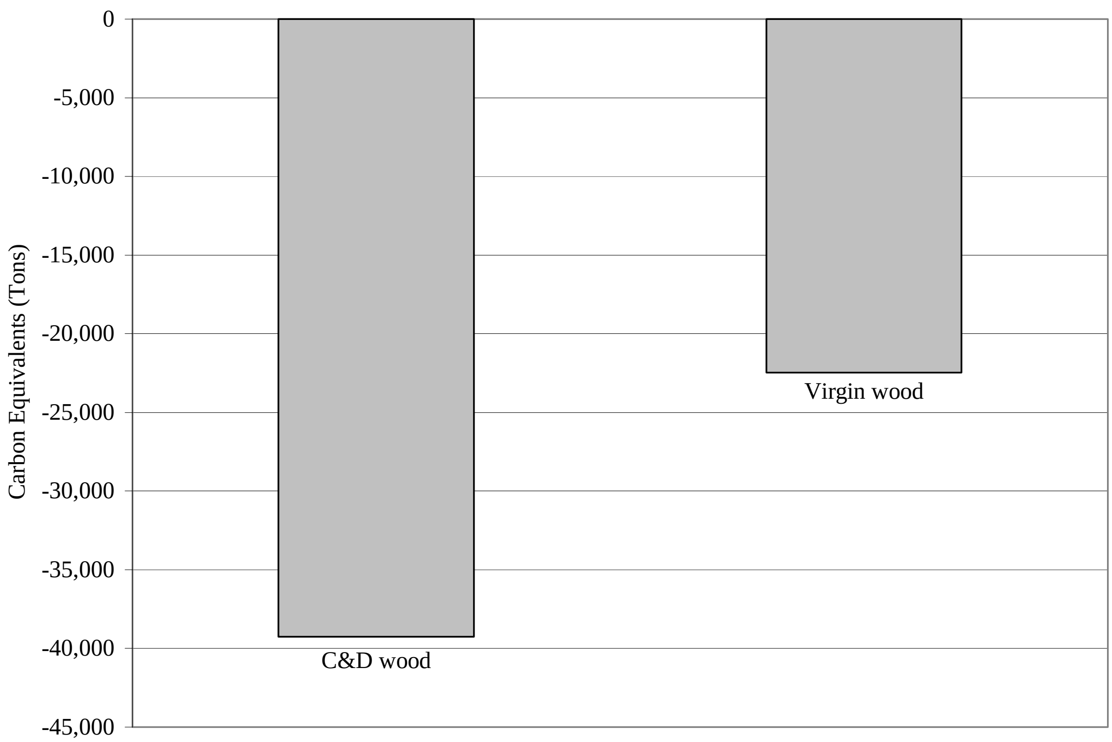

Figure 34. Carbon Emissions C&D Wood versus Virgin Wood (Tons/yr)

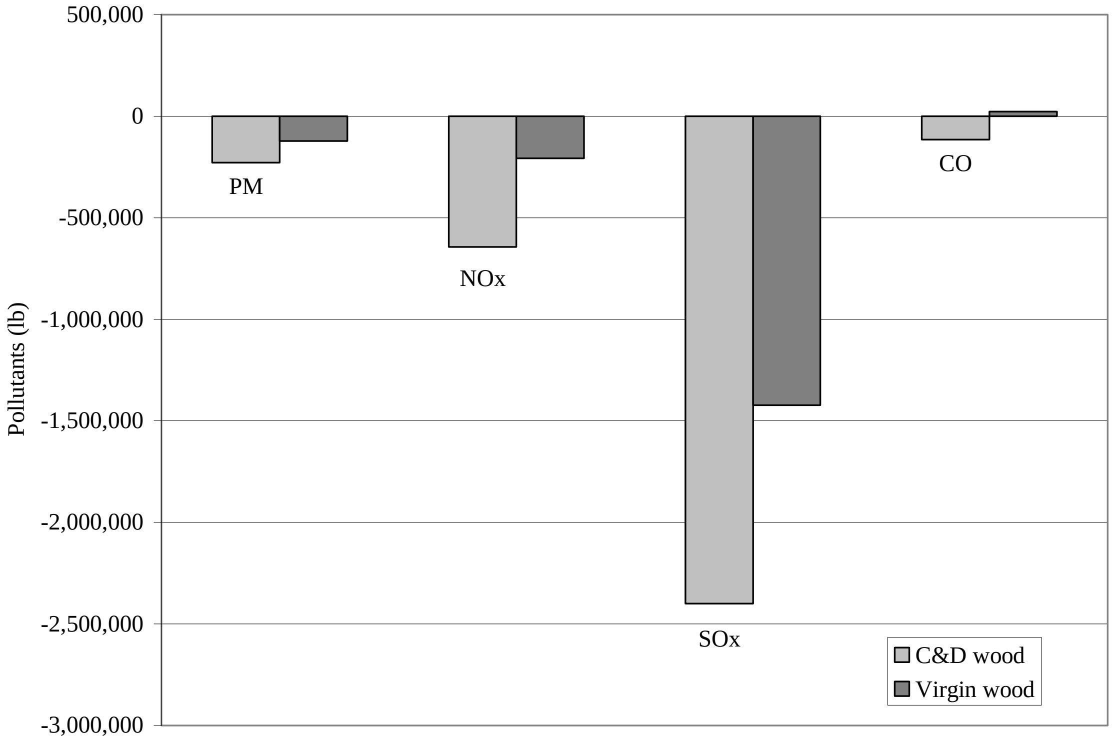

Figure 35. Air Emissions C&D Wood versus Virgin Wood (lb/yr)

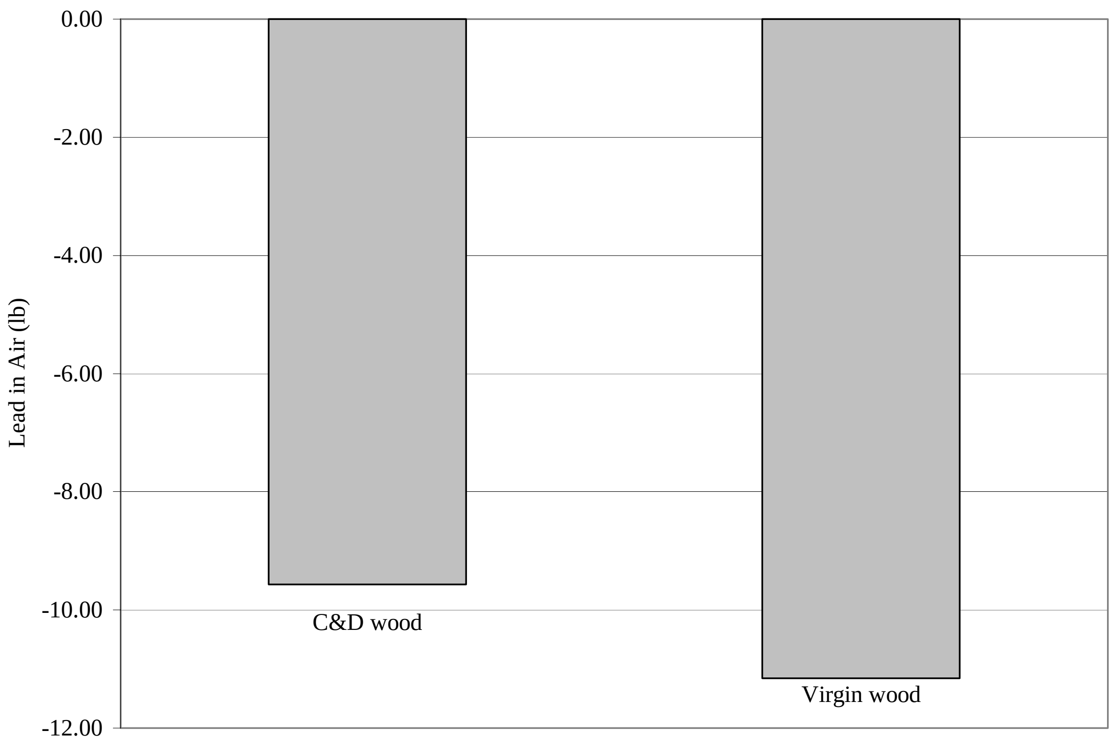

Figure 36. Lead in Air Emissions C&D Wood versus Virgin Wood (lb/yr)

5.0 SUMMARY

To provide assistance in quantifying trade-offs for the management and utilization of C&D wood waste in New Hampshire, UNH conducted an LCA of various management options using the U.S. Environmental Protection Agency's Municipal Solid Waste Decision Support Tool (MSW DST). Adjustments to the MSW DST were made to more accurately model the management of C&D debris and C&D wood. The metal concentration of the C&D wood product was increased, as well as the energy (BTU) content. Details of how the MSW DST was modified are contained in Section 3. Seven different C&D management related scenarios were input into the tool based upon the annual production of 702,000 tons/yr of C&D debris in the state of New Hampshire,.

1. C&D debris is transported to a local processing/recycling facility, 83% is recycled or reused (cardboard and metal recycled), 17% disposed in a landfill with landfill gas flared, the wood fraction is combusted with energy recovery at out-of-state facilities an average of 140 miles away offsetting the NE power grid.
2. C&D debris is transported to a local processing/recycling facility, 83% is recycled or reused (cardboard and metal recycled), 17% disposed in a landfill with landfill gas flared, the wood fraction is combusted with energy recovery at a local facility 25 miles away offsetting the NE power grid.
3. C&D debris is transported to a local processing/recycling facility, 83% is recycled or reused (cardboard and metal recycled), 17% disposed in a landfill with landfill gas flared, the wood fraction is combusted with energy recovery at a local facility 25 miles away offsetting 100% coal.
4. C&D debris is transported to a local processing/recycling facility, 83% is recycled or reused (cardboard and metal recycled), 17% disposed in a landfill with landfill gas flared, the wood fraction is landfilled and gas is flared.
5. C&D debris is transported to a local processing/recycling facility, 83% is recycled or reused (cardboard and metal recycled), 17% disposed in a landfill with landfill gas flared, the wood fraction is landfilled and gas is used to make energy offsetting the NE power grid.
6. C&D debris is transported to a local landfill, disposed and gas is flared.
7. C&D debris is transported to a local landfill, disposed and gas is used to make energy offsetting the NE power grid.

Additionally, a scenario was developed to compare the combustion of virgin wood from northern New Hampshire with locally produced C&D wood. The virgin wood is transported a distance of approximately 150 miles, the energy generated offsets the NE power grid and the virgin wood ash is beneficially used (not landfilled). This scenario is compared to Scenario 2 outlined above after the wood product leaves the C&D processing facility. The tonnage used for this comparison is 280,000 tons of wood, based upon the annual production of C&D wood in New Hampshire.

For the first set of comparisons, results were obtained for energy consumption, carbon emissions, criteria air pollutants, ancillary solid waste produced, and organic and inorganic constituents in water (details contained in Section 4). LCA illustrates trade-offs through examining impacts and benefits. Negative results illustrate the "offsetting" of this amount of emission. Not only do negative results mean that emission of this constituent is avoided, it conceptually means that this constituent is reduced below what is currently being released. For example, negative carbon emissions, would result in carbon credits (that may eventually be able to be sold as long as they are considered in renewable portfolio standards).

As shown in the results section (Section 4), the C&D recycling facility and combustion of the C&D wood with energy recovery and offsetting the NE energy grid or coal result in positive benefits and offsets. In the outranking of scenarios (Section 4.7), all scenarios with wood waste combustion with energy recovery had lower impact rankings than the others. The C&D recycling-only scenarios resulted in less overall impact than the disposal-only scenarios. For the disposal scenarios, the landfill gas-to-energy scenario has more offsets than the flared landfill gas. This ranking indicates which scenario provided the lowest impacts most frequently and is clear from the results that C&D recycling facilities provide many environmental benefits to the state of New Hampshire and when viewed in concert with the combustion of C&D wood with energy recovery additional environmental benefits are achieved.

The benefits afforded by C&D recycling and combustion of the wood fraction for energy production have significant ramifications. For example, recycling C&D debris and combustion of C&D wood with energy recovery produces a net gain in energy of over 7,000,000 MBTU – enough to power 191,000 homes in New Hampshire. Similarly, 70,000 to 130,000 tons/yr of carbon emissions are eliminated; 130,000 tons of carbon equivalent emissions are approximately equal to the annual carbon emissions from the electricity used by 55,000 households (using EPA's Greenhouse Gas Equivalency Calculator). Criteria air pollutants are significantly reduced as well when combusting C&D wood with energy recovery producing 600 tons/yr less particulate matter, 430 tons/yr less of nitrogen oxides, 2,300 tons/yr less of sulfur oxides, 890 tons/yr less of carbon monoxide and 10 pounds/yr less of lead (with NE power grid off-set) when compared to landfilling.

When C&D wood combustion was compared with virgin wood combustion, it was found that C&D wood combustion had lower environmental impacts. While combustion of virgin wood and C&D wood both produce energy, the C&D wood combustion produces over 1.2 million MBTU more energy for the same amount of wood (280,000 tons) when compared to virgin wood combustion with energy recovery. This is enough extra energy to power over 33,000 homes for one year. Additionally the carbon offsets are higher for C&D wood – by 16,700 tons of carbon equivalents (like taking 11,000 passenger cars off the road for 1 year). Based upon best available air pollution technologies and a wood tonnage of 280,000tons/yr, the C&D wood used for energy production produces: 50 tons/yr less particulate matter, 200 tons/yr less of nitrogen oxides, 485 tons/yr less of sulfur oxides, and 69 tons/yr less of carbon monoxide when compared to virgin wood. Additionally, it results in a reduction of lead, over 9 lb only ~1.5 different than virgin wood.

Many of the off-sets discussed in this report come from the fact that the wood is a source of energy and it offsets traditional energy sources when it is used for energy production.

Both virgin wood and C&D wood can be considered biogenic alternative energy sources. The use of alterative energy sources will likely continue to increase and this analysis illustrates that C&D wood waste can contribute to an integrated alternative energy portfolio.

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Appendix A – Internal RTI document for metal volatilization estimates

Estimating Municipal Waste Combustor Metal Air Emissions as a Function of Waste Composition

Kenneth W. Harrison and **Morton A. Barlaz**, Department of Civil Engineering, North Carolina State University, Raleigh, NC 27695, Ph: 919-541-7676, email: barlaz@unity.ncsu.edu

Subba R. Nishtala, Center for Environmental Analysis, Research Triangle Institute, Cornwallis Road, Research Triangle Park, NC 27709, Ph: 919-541-7448, email: nsr@rti.org

Abstract

The purpose of this paper is to present an allocation scheme for assigning metal air emissions from combustion to individual constituents of municipal solid waste (MSW). The allocation scheme will be used to model emissions from mixed waste as a function of the composition of waste, and to investigate the effect of including or excluding a waste constituent from the waste mix to be combusted. The methodology proposed here assumes that the mass emission rate of a metal will be directly proportional to its input to the combustor provided it does not exceed regulated limits. The fraction of a metal that volatilizes and escapes through the stack is assumed to be the same across waste categories. The proposed allocation scheme is used to derive air emissions factors for combustion of individual constituents of the waste stream, and will be used as part of an overall effort to use life-cycle management to evaluate integrated MSW management strategies.

Introduction

The purpose of this paper is to present an allocation scheme for assigning metal air emissions from combustion to individual constituents of the MSW stream. This paper presents a methodology for estimating metals emissions for any mixture of solid waste entering a municipal solid waste combustor. Relating emissions to waste composition is necessary to evaluate the environmental implications of integrated solid waste management alternatives that include combustion. For example, the waste composition combusted will depend upon the degree of recycling and composting. Alternative approaches for estimating emissions factors (EFs) of metals from waste combustion are discussed before describing the approach taken.

Alternative approaches for estimating uncontrolled emission factors

Metals in solid waste can volatilize and be released to the atmosphere when waste is combusted. The amount of the metal that volatilizes and escapes through the air pollution control equipment is a complex function of how the metal is bound to the waste, the temperatures attained during combustion, and other physical and chemical factors. Due to limited understanding of these processes, we cannot mechanistically model metals emissions [1]. The next best option would be to use statistical models that associate metal emissions to waste component inputs. The only accepted statistical study that attempts to do this is the Burnaby report [2]. Unfortunately, the statistical results contained in the Burnaby report are insufficient for developing a sound approach for estimating metals emissions for all possible waste mixtures.

The limitation of the data produced in the Burnaby study lies in its experimental design. The study attempted to relate metal emissions to natural day-to-day variation in waste composition. For those waste categories for which there was ample day-to-day variation, and the actual contribution of metals emissions was sufficiently large, statistical significance was found. However, the variation in waste composition was small for many waste categories. As a result, statistically significant relationships between many waste components and metals could not be demonstrated. The limited statistical information prevented identification of most of the important relationships. The Burnaby study concludes: "Failure to implicate a component does not mean that it is not a significant source. It simply means that either the unidentified component was relatively constant between runs or metals analyses were not done." ("Conclusions", Burnaby final report [2], Volume II, Section 11, page 11-14.)

In light of the deficiencies of the Burnaby study for the purpose at hand, it would be incorrect to attribute emissions only to the waste components for which statistical significance was found. Alternative options for estimating EFs include:

1. Assume emissions vary only with the mass, not the composition, of solid waste entering the combustor.
2. Develop metals emission factors based on metals composition of individual waste components. Assume that emissions attributed to a waste component are in proportion to its metals content.
3. For each waste component, develop factors that reflect the relative ability of the metals to be released.

Each of these options has drawbacks. The first approach is the simplest and probably most common approach used thus far. It assumes that metal emissions per unit of mass of solid waste are the same across waste types, regardless of whether the waste type contains any of that metal. The second approach is somewhat more sophisticated. However, it assumes that the tendency of a metal to volatilize and escape through the stack is the same regardless of how it is bound to the waste. The third approach would require much subjective input based on very little evidence.

In this paper we use the second approach that assumes that metals emissions vary with metals input. We selected this approach because adequate data on relative ability of metals to be released from waste components are not available. We propose that the adopted approach is better than allocation of metals by mass uniformly across all waste components. The specific methodology for determining emission factors by waste constituent is described below.

Methodology for calculating uncontrolled metals emission factors

The basic assumption underlying the methodology proposed here is that the mass emission rate of a metal will be directly proportional to its input to the combustor. The fraction of a metal that volatilizes and escapes through the stack is assumed to be the same across waste categories. The analysis relies on the Burnaby study to develop uncontrolled emission factors for each waste category and for each metal. Specifically, the analysis relies on data from Burnaby study, including 1) the elemental metal content for each of 60 waste categories, 2) waste composition, 3) the total mass feed rate, and 3) emissions monitoring data.

Table 1 presents the waste composition and metals content for 11 metals and 60 waste categories. From the information in Table 1, the total input of each metal to the combustor was calculated per 1000 kg waste. In addition to metals input, the corresponding metals emissions (prior to control) needed to be determined. Column 1 of Table 2 presents the uncontrolled emission rates of the metals. The uncontrolled emission rates were calculated from the flow rate data reported in Table C-4 of the Burnaby study and the inlet measurements of metals concentrations presented in Table C-5 of the Burnaby study. By dividing the emission rates (column 1, Table 2) by the rate at which waste was fed to the combustor during the study period, the uncontrolled emissions per 1000 kg was determined (column 2, Table 2). Finally, dividing the uncontrolled emissions per 1000 kg by the metal input per 1000 kg lead to an estimate of the fraction of metal that partitions to the flue gas (column 3, Table 2). The main assumption of this methodology is that this fraction is the same across waste categories. With this key assumption, these partitioning fractions (column 3, Table 2) were applied to the metal content of each waste category leading to the uncontrolled emission factors shown in Table 3. The values in Table 3 have been converted to units of lbs metal per ton waste combusted.

The methodology described above is illustrated in the following example. Using a 1,000 kg MSW waste sample, and office paper and lead as an example, the steps involved in developing the uncontrolled emission factors for each waste category and metal are as follows: First, find the amount of office paper in a 1,000 kg MSW sample using the percent composition data (column 3, Table 1). This amount is 26.9 kg office paper (2.69%*1000). Next, using the lead content data from Table 1, determine the amount of lead input to the incinerator from the office paper in the sample. In the 26.9 kg office paper, there is estimated to be 0.121 g lead (4.5*26.9/1000). Similarly, calculate the lead input for the remaining waste components and sum to determine the total lead input. The total lead input in the 1000 kg sample was 188 g. Next, from the average uncontrolled lead emission rate (4.80 g/min) and the average feed rate to the combustor over the course of the Burnaby study (0.487 kg/min), determine the average uncontrolled emissions of lead from the 1000 kg MSW. This value is 9.86 g lead emitted (uncontrolled). Next, calculate the ratio of uncontrolled lead emissions per g lead input. The resulting value is 0.0525 g lead emitted per g lead input (9.86 g/188 g).

According to this methodology, this value is assumed to be constant across waste categories. Uncontrolled lead emissions attributable to the office paper in the 1000 kg

MSW sample is calculated to be 0.006353 g lead (0.0525*0.121 g). Finally, an emission factor for office paper can be developed by dividing this amount by the mass of office paper in the 1000 kg sample. According to the methodology, absent control devices, 236 micrograms lead are emitted per kg of office paper combusted (0.006353*1000000/26.9).

Controlled emissions for any waste mix can be estimated from the uncontrolled emission factors developed above and metal removal efficiencies of air pollution control equipment. For example, controlled emissions for lead are calculated as follows:

Equation 1

$$Emissions_{Pb} = \left(1 - Removal\_efficiency_{Pb}\right) \cdot \sum_i TPD_i \cdot Uncontrolled\_EF_{Pb,i}$$

$Emissions_{Pb}$ refers to the pounds of daily lead emissions from the combustor. TPD_i is the tons per day of waste component i combusted. $Uncontrolled\_EF_{Pb,i}$ is the lead emission factor for waste component i, and $Removal\_efficiency_{Pb}$ is the removal efficiency of lead.

To illustrate how Equation 1 can be applied to estimate the emissions of a different waste mix, consider a combustor processing 1000 tons per day—800 tons newsprint and 200 tons PET plastic. According to Table 3, the uncontrolled emission factor for glued newsprint is 2.52E-04 lbs Pb/ton newsprint and for PET, 6.46E-03 lbs Pb/ton PET. Assuming a removal efficiency of 99.9%, the controlled lead emissions from the combustor as calculated using Equation 1 is (1-0.999)*(800* 2.52E-04 +200*6.46E-03), or 0.0015 lbs lead emitted per day.

Conclusions

This paper has presented one approach for estimating metals emissions from a municipal waste combustor as a function of the waste mix combusted. Fundamental to the approach is an assumption that a fixed fraction of a metal's input to the combustor will partition to the flue gas and that this fraction is the same across waste components. By assuming a removal efficiency, an estimate of the emissions from the combustion of any waste mix can be realized. The albeit simplified approach was pursued only after failing to find studies based on statistical or mechanistic analysis that could relate emissions to waste composition. By considering the metals content of the waste components, the paper represents an improvement over current practice that estimates metals emissions in proportion to the total mass waste combusted. In future work, this methodology will be applied to investigate how combustor emissions change as other waste management options (including composting and recycling) change the composition and quantity of waste combusted.

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EPA or DOE policy and are not intended to be used to make judgments about which material, product, or management practice is environmentally preferable.

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Table 1. Burnaby waste characterization and metals content for selected metals (g metal/ 1000 kg waste component) [2]

Major category	Minor category	Fraction of MSW (%)	As	Cd	Hg	Pb	Zn
PAPER							
fine/ comp/ office		2.69	1.3	0.1	0.3	4.5	208
books		30	0.4	0.4	0.2	0.005	88
magazines	glued	1.01	1.1	0.001	0.3	0.4	36
	not glued	0.92	1.8	0.3	0.3	5.9	18
laminates	wax/ plastic	1.6	0.7	0.3	0.1	7.1	16
	foil	0.25	0.8	0.1	0.1	92.3	119
newsprint	glued	0.44	0.8	0.1	0.3	2.4	8
	notglued (b&w)	4.05	0.7	0.1	2.9	7.2	19
	color	1.37	0.6	0.1	0.3	5.7	29
browns	corrugate	7.4	0.6	0.1	0.1	3.8	10
	kraft	1.98	0.8	0.1	0.5	9.3	22
	box board	1.26	0.7	0.2	0.2	12	29
residual mixed		14.5	1.2	1.7	0.4	229.4	81
PLASTIC							
film	color	2.99	0.5	6.6	0.2	361.5	1132
	flexible	2.56	0.7	2.8	0.2	279.3	67
	rigid	0.42	0.3	37.2	0.1	33.7	52
food/ beverage/ household	1 (PET)	0.08	0.8	5.3	0.2	61.5	97
	2 (HDPE)	0.3	0.5	2.9	0.2	60.6	142
	3 (PVC)	0.02	0	4.5	0.1	2160	3
	4 (LDPE)	0.01	0.2	2.5	0.1	56	89
	5 (PP)	0.06	0.5	1.9	0.1	69.3	40
	6 (PS)	0.02	0.2	4.7	0.1	25	98
	non-identified	0.86	1.2	79.3	0.4	157.7	273
houseware	clear	0.07	0.1	0.9	0.1	61.7	108
	white	0.34	0.2	2.5	0.2	41.8	129
	blue	0.07	3.1	289.7	0.1	64.3	76
	yellow	0.1	0.3	104.8	0.1	2479	277
	other	0.84	0.3	100.9	0.3	647.3	199
toys and other		0.43	0.5	75.8	0.1	102.6	349
video tape/ film		0.01	14.3	2195	0.2	882	774
ORGANICS							
yard & garden	lawn/ plant	11.23	7.3	6	1.4	153.6	365
	branches	2.89	0.9	1.1	0.4	61.9	124
food waste	organic	6.06	1.2	2	0.3	72	186
wood	finished	3.54	5.1	1.1	0.2	562.9	117
	unfinished	4.65	34	0.04	0.4	324.3	205
textiles		4.44	0.4	2.8	1.1	126.2	142
footwear		0.93	0.7	11.9	0.1	133.8	764
METALS							
ferrous	beer	0.05	8.8	61.9	36.4	230.5	886
	soft drink	0.03	8.8	61.9	36.4	230.5	886
	food	1.09	7	43.1	5.6	344.3	4566
	band & strap	0.18	40	15	0.02	596	30
	elect motor	1.93	9480	9.1	5.4	609.6	7332
non-ferrous	beer	0.07	0.2	3	0.3	68	170
	soft drink	0.11	0.4	6	0.4	32.3	248
	food	0.16	7215	1.7	0.2	95.5	445
	manufd.	0.52	199	5.6	0.2	94	4.E+05
	foil/ pack	0.21	0.8	51	0.8	0.004	120
	other	0.05	8389	2	0.2	111	518

[1]Source: [1], Table 9-5

Table 1. Burnaby waste characterization and metals content for selected metals (g metal/ 1000 kg waste component) [2], continued

Major category	Minor category	Fraction of MSW (%)	As	Cd	Hg	Pb	Zn
GLASS							
combined	clear	1.45	1	4.8	0.2	109.3	60
	green	0.23	9.8	0.3	0.1	20	21
	brown	0.21	6.9	1.7	0.6	103.1	251
	other color	0.04	0.4	5.4	0.1	90	1671
INORGANIC							
light construction	rock/ sand/ dirt/ concrete/ ceramic	0.96	6	20	0.3	1545	5118
	drywall/ plaster	0.1	0.6	2	0.3	38	21
	insulation	0.004	0.7	0.05	1.1	40.8	12
	other	0.7	17.1	0.4	0.1	30.1	57
Small appliances							
electrical parts	plastic	0.58	777.1	3.6	0.1	662.3	63
Household hazardous							
batteries	carbon	0.05	2.8	31	20.5	40	63000
	ni-cad	0.004	4.4	120000	0.3	113	685
	alkaline	0.04	1	1940	242	143	1E+05
Fines		7.83	6.6	4.4	1.4	258.5	854
Total		97.288					

[1]Source: [2], Table 9-5

Table 2. Average uncontrolled emission rates (micrograms metal/min), uncontrolled emissions (micrograms/1000 kg MSW), and uncontrolled emission fraction (micrograms metal emitted/ g metal input)

Metal[a]	Uncontrolled emission rate[b] (micrograms/min)	Uncontrolled emissions[c] (micrograms/ 1000 kg MSW burned)	Uncontrolled emission fraction[d] (micrograms metal emitted/g metal input)
As	179,018	367,322	1,764
Cd	672,265	1,379,398	121,941
Hg	221,397	454,277	492,194
Pb	4,803,888	9,856,938	52,550
Zn	29,688,491	60,916,824	23,187

Source for inlet metals concentrations: For Hg: Table 4, Hg Summary (mg/dscm @ 11% O2), pg. 14 of Emission Survey Monitoring Report, Vol. IV, Sect. 4 of Burnaby report. For all other metals: Table 3, Multimetal Stack Metal Concentrations (micrograms/dscm @ 11% O2), pg. 13 of Emission Survey Monitoring Report, Vol. IV, Sect. 4 of Burnaby report.

a) The metals concentrations for all but mercury were measured by the multimetals method.
b) Average of the products of the inlet metals concentration (micrograms/dscm) and adjusted inlet flow rates (dscm/min) from Table C-4.
c) Uncontrolled emission rate (micrograms/min) divided by the feed rate 0.487 * 1000 kg MSW burned/min (from Table C-3).
d) Uncontrolled emissions (micrograms/1000 kg MSW) divided by the total metals input (g metal input/1000 kg MSW) from Table C-2.

Table 3. Uncontrolled emission factors (lbs metal /ton waste component)

Major category	Minor category	As	Cd	Hg	Pb	Zn
PAPER						
fine/ comp/ office		4.59E-06	2.44E-05	2.95E-04	4.73E-04	9.65E-03
books		1.41E-06	9.76E-05	1.97E-04	5.26E-07	4.08E-03
magazines	glued	3.88E-06	2.44E-07	2.95E-04	4.20E-05	1.67E-03
	not glued	6.35E-06	7.32E-05	2.95E-04	6.20E-04	8.35E-04
laminates	wax/ plastic	2.47E-06	7.32E-05	9.84E-05	7.46E-04	7.42E-04
	foil	2.82E-06	2.44E-05	9.84E-05	9.70E-03	5.52E-03
newsprint	glued	2.82E-06	2.44E-05	2.95E-04	2.52E-04	3.71E-04
	notglued (b&w)	2.47E-06	2.44E-05	2.85E-03	7.57E-04	8.81E-04
	color	2.12E-06	2.44E-05	2.95E-04	5.99E-04	1.34E-03
browns	corrugate	2.12E-06	2.44E-05	9.84E-05	3.99E-04	4.64E-04
	kraft	2.82E-06	2.44E-05	4.92E-04	9.77E-04	1.02E-03
	box board	2.47E-06	4.88E-05	1.97E-04	1.26E-03	1.34E-03
residual mixed		4.23E-06	4.15E-04	3.94E-04	2.41E-02	3.76E-03
PLASTIC						
film	color	1.76E-06	1.61E-03	1.97E-04	3.80E-02	5.25E-02
	flexible	2.47E-06	6.83E-04	1.97E-04	2.94E-02	3.11E-03
	rigid	1.06E-06	9.07E-03	9.84E-05	3.54E-03	2.41E-03
food/ beverage/ household	1 (PET)	2.82E-06	1.29E-03	1.97E-04	6.46E-03	4.50E-03
	2 (HDPE)	1.76E-06	7.07E-04	1.97E-04	6.37E-03	6.59E-03
	3 (PVC)	0.00E+00	1.10E-03	9.84E-05	2.27E-01	1.39E-04
	4 (LDPE)	7.05E-07	6.10E-04	9.84E-05	5.89E-03	4.13E-03
	5 (PP)	1.76E-06	4.63E-04	9.84E-05	7.28E-03	1.85E-03
	6 (PS)	7.05E-07	1.15E-03	9.84E-05	2.63E-03	4.54E-03
	nonidentified	4.23E-06	1.93E-02	3.94E-04	1.66E-02	1.27E-02
houseware	clear	3.53E-07	2.19E-04	9.84E-05	6.48E-03	5.01E-03
	white	7.05E-07	6.10E-04	1.97E-04	4.39E-03	5.98E-03
	blue	1.09E-05	7.07E-02	9.84E-05	6.76E-03	3.52E-03
	yellow	1.06E-06	2.56E-02	9.84E-05	2.61E-01	1.28E-02
	other	1.06E-06	2.46E-02	2.95E-04	6.80E-02	9.23E-03
toys and other		1.76E-06	1.85E-02	9.84E-05	1.08E-02	1.62E-02
video tape/ film		5.04E-05	5.35E-01	1.97E-04	9.27E-02	3.59E-02
ORGANICS						
yard & garden	lawn/ plant	2.57E-05	1.46E-03	1.38E-03	1.61E-02	1.69E-02
	branches	3.17E-06	2.68E-04	3.94E-04	6.51E-03	5.75E-03
food waste	organic	4.23E-06	4.88E-04	2.95E-04	7.57E-03	8.63E-03
wood	finished	1.80E-05	2.68E-04	1.97E-04	5.92E-02	5.43E-03
	unfinished	1.20E-04	9.76E-06	3.94E-04	3.41E-02	9.51E-03
textiles		1.41E-06	6.83E-04	1.08E-03	1.33E-02	6.59E-03
footwear		2.47E-06	2.90E-03	9.84E-05	1.41E-02	3.54E-02
METALS						
ferrous	beer	3.10E-05	1.51E-02	3.58E-02	2.42E-02	4.11E-02
	soft drink	3.10E-05	1.51E-02	3.58E-02	2.42E-02	4.11E-02
	food	2.47E-05	1.05E-02	5.51E-03	3.62E-02	2.12E-01
	band & strap	1.41E-04	3.66E-03	1.97E-05	6.26E-02	1.39E-03
	elect motor	3.34E-02	2.22E-03	5.32E-03	6.41E-02	3.40E-01
non-ferrous	beer	7.05E-07	7.32E-04	2.95E-04	7.15E-03	7.88E-03
	soft drink	1.41E-06	1.46E-03	3.94E-04	3.39E-03	1.15E-02
	food	2.54E-02	4.15E-04	1.97E-04	1.00E-02	2.06E-02
	manufd.	7.02E-04	1.37E-03	1.97E-04	9.88E-03	1.85E+01
	foil/ pack	2.82E-06	1.24E-02	7.88E-04	4.20E-07	5.56E-03
	other	2.96E-02	4.88E-04	1.97E-04	1.17E-02	2.40E-02

Table 3. Uncontrolled emission factors (lbs metal /ton waste component), continued

Major category	Minor category	As	Cd	Hg	Pb	Zn
GLASS						
combined	clear	3.53E-06	1.17E-03	1.97E-04	1.15E-02	2.78E-03
	green	3.46E-05	7.32E-05	9.84E-05	2.10E-03	9.74E-04
	brown	2.43E-05	4.15E-04	5.91E-04	1.08E-02	1.16E-02
	other color	1.41E-06	1.32E-03	9.84E-05	9.46E-03	7.75E-02
INORGANIC						
light construction	rock/ sand/ dirt/ concrete/ ceramic	2.12E-05	4.88E-03	2.95E-04	1.62E-01	2.37E-01
	drywall/ plaster	2.12E-06	4.88E-04	2.95E-04	3.99E-03	9.74E-04
	insulation	2.47E-06	1.22E-05	1.08E-03	4.29E-03	5.56E-04
	other	6.03E-05	9.76E-05	9.84E-05	3.16E-03	2.64E-03
Small appliances						
electrical parts	plastic	2.74E-03	8.78E-04	9.84E-05	6.96E-02	2.92E-03
Household hazardous						
batteries	carbon	9.88E-06	7.56E-03	2.02E-02	4.20E-03	2.92E+00
	Ni-Cd	1.55E-05	2.93E+01	2.95E-04	1.19E-02	3.18E-02
	alkaline	3.53E-06	4.73E-01	2.38E-01	1.50E-02	6.49E+00
Fines		2.33E-05	1.07E-03	1.38E-03	2.72E-02	3.96E-02