Energy Usage and Emissions Associated with Remanufacturing as Part of a Solid Waste Management Life Cycle Inventory Model

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

Management of municipal solid waste (MSW) through the unit operations of collection, transfer, separation, remanufacturing, combustion and landfilling forms a complex interrelationship of mass flows with associated costs, energy consumption, solid waste production and airborne and waterborne emissions. To examine these interrelationships and identify potential optimal mass flows and synergistic benefits among unit operations, it is necessary to quantify the costs, energy consumption and emissions associated with each unit operation of interest.

The work described here is a part of a larger project that will examine these life cycle inventory (LCI) parameters for a large number of possible unit operations for 38 distinct components of MSW. The ultimate objective of this larger project is the development of a computer based decision support system (DSS) to allow a user to examine interrelationships among LCI parameters and to explore optimal MSW management strategies with regard to minimization of selected parameters such as CO_2 emissions or energy consumption. Additional objectives are to develop an LCI database to support the DSS and to apply the DSS to case studies. The LCI model and the associated remanufacturing implications are discussed in Section 2.

In a smaller related research project, process models were developed to account for the total energy usage and emissions (pre-combustion and combustion) resulting from the use of electric energy, as well as the transportation energy and process energy used in the virgin manufacturing and remanufacturing processes for corrugated boxes, newsprint and aluminum cans. (Ultimately, this effort will be expanded to include all 28 recyclable components designated for the waste stream as a part of the overall project.) Two separate process models were developed: one to address energy usage and emissions associated with electric energy consumption and one to address energy usage and emissions associated with remanufacturing processes. This report addresses the remanufacturing process model.

The remanufacturing process model is described in Section 3. It provides energy usage and emissions on a per ton basis for virgin and re-manufactured materials. At this point in the project, the remanufacturing process model covers only corrugated boxes, newsprint and aluminum. Where a user believes that the national fuel mix does not properly represent the mix used in a remanufacturing process, fuel biasing provides the capability for certain fuels to be more heavily weighted.

Throughout this document, many tables contain entries labeled “variable name.” These variable names are the names by which that particular table entry is referenced by other process models and by the LCI model.

2. The Solid Waste Management LCI Model

2.1 Model Overview

The ultimate objective of the overall project is the development of a user friendly decision-making tool that allows users to perform cost and LCI optimization modeling of their existing solid waste management system, entirely new systems or some combination of both. The processes that can be modeled include waste generation, source reduction, collection and transfer, separation (material recovery facilities—MRFs and drop-off facilities), treatment (including composting, anaerobic digestion, combustion and refuse-derived fuel production) and disposal (landfill or enhanced bioreactor).

Figure 2-1 provides an overview of potential mass flows through a solid waste management system. As can be seen from this figure, upstream decisions can affect the viability of implementing various downstream processes. For example, aggressive upstream recycling of paper would affect the viability of a downstream combustion facility. Because of the large number of mass flow interrelationships, effective evaluation of alternatives, in the absence of a modeling tool, would be a daunting task for a solid waste planner.

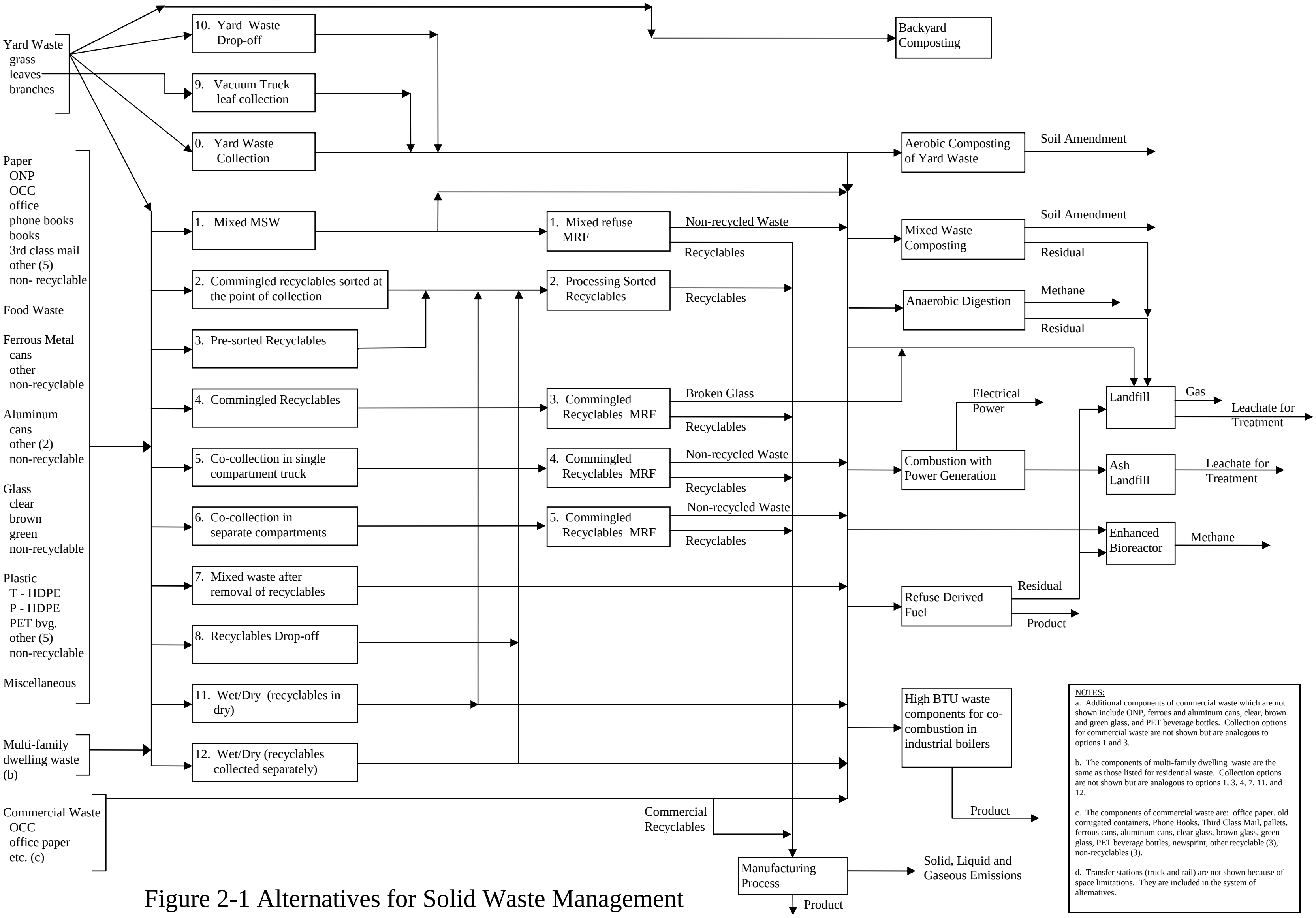
The DSS being developed under this project will allow the user to perform cost and LCI analysis and optimization based on user-specified data on MSW generation. Existing facilities and/or equipment can be incorporated as model constraints to ensure that previous capital expenditures are not negated by the model solution.

As shown in Figure 2-2, the DSS consists of several components including process models, an optimization module and a graphic user interface (GUI). The process models consist of a set of process models developed in Microsoft Excel. These process models use a combination of default and user supplied data to calculate the cost and life cycle coefficients on a per unit mass basis for each of the 38 MSW components being modeled for each solid waste management unit process (collection, transfer, etc.). For example, in the electric energy process model, the user is asked to specify the fuel mix used to generate electricity in the geographic region of interest. Based on this design information and the emissions associated with generating electricity from each fuel type, the process model calculates coefficients for emissions related to the use of a kilo-watt hour of electricity. These emissions are then assigned to waste stream components on a mass basis for any facility that uses electricity and through which the mass flows. For example, MRFs use electricity for conveyors and lighting. The emissions associated with electricity generation would be assigned to the mass that flowed through that facility. To the extent possible, the ability for the user to override default data has been incorporated.

The optimization module is implemented using the CPLEX linear programming solver. The model is constrained by mass flow equations. These mass flow constraints preclude impossible or nonsensical model solutions. For example, these mass flow constraints will exclude the possibility of removing aluminum from the waste stream via a mixed waste MRF and then sending the aluminum to a landfill. The user can identify the objective as minimizing total cost or any LCI parameter (Particulate matter, NO_x, SO_x, CO, CO_2, and CH_4). The optimization module uses linear programming techniques to determine the optimum solution consistent with the user-specified objective and mass flow and user-specified constraints. Examples of user-specified constraints are the use of existing equipment/facilities and a minimum recycling percentage requirement.

The GUI consists of Microsoft visual basic routines that act to pull all components of the model together to allow easy user manipulation of the process model models and the optimization module. It allows additional user constraints to be specified and provides a graphical representation of the solid waste management alternatives resulting from the optimization.

The various process model process models can be used in a stand alone fashion to examine issues such as the total energy consumption associated with a given generation fuel mix. However, the ultimate intent of the DSS is that the existence of these process models be transparent to the user and that all user interaction take place through the DSS GUI depicted in Figure 2-2. Also, the decision support system can be used as an accounting tool for existing solid waste management systems. When used in this mode, no optimization is performed; rather, the cost and LCI values for user-specified management strategies are evaluated.



NOTES:

a. Additional components of commercial waste which are not shown include ONP, ferrous and aluminum cans, clear, brown and green glass, and PET beverage bottles. Collection options for commercial waste are not shown but are analogous to options 1 and 3.

b. The components of multi-family dwelling waste are the same as those listed for residential waste. Collection options are not shown but are analogous to options 1, 3, 4, 7, 11, and 12.

c. The components of commercial waste are: office paper, old corrugated containers, Phone Books, Third Class Mail, pallets, ferrous cans, aluminum cans, clear glass, brown glass, green glass, PET beverage bottles, newsprint, other recyclable (3), non-recyclables (3).

d. Transfer stations (truck and rail) are not shown because of space limitations. They are included in the system of alternatives.

Figure 2-1 Alternatives for Solid Waste Management

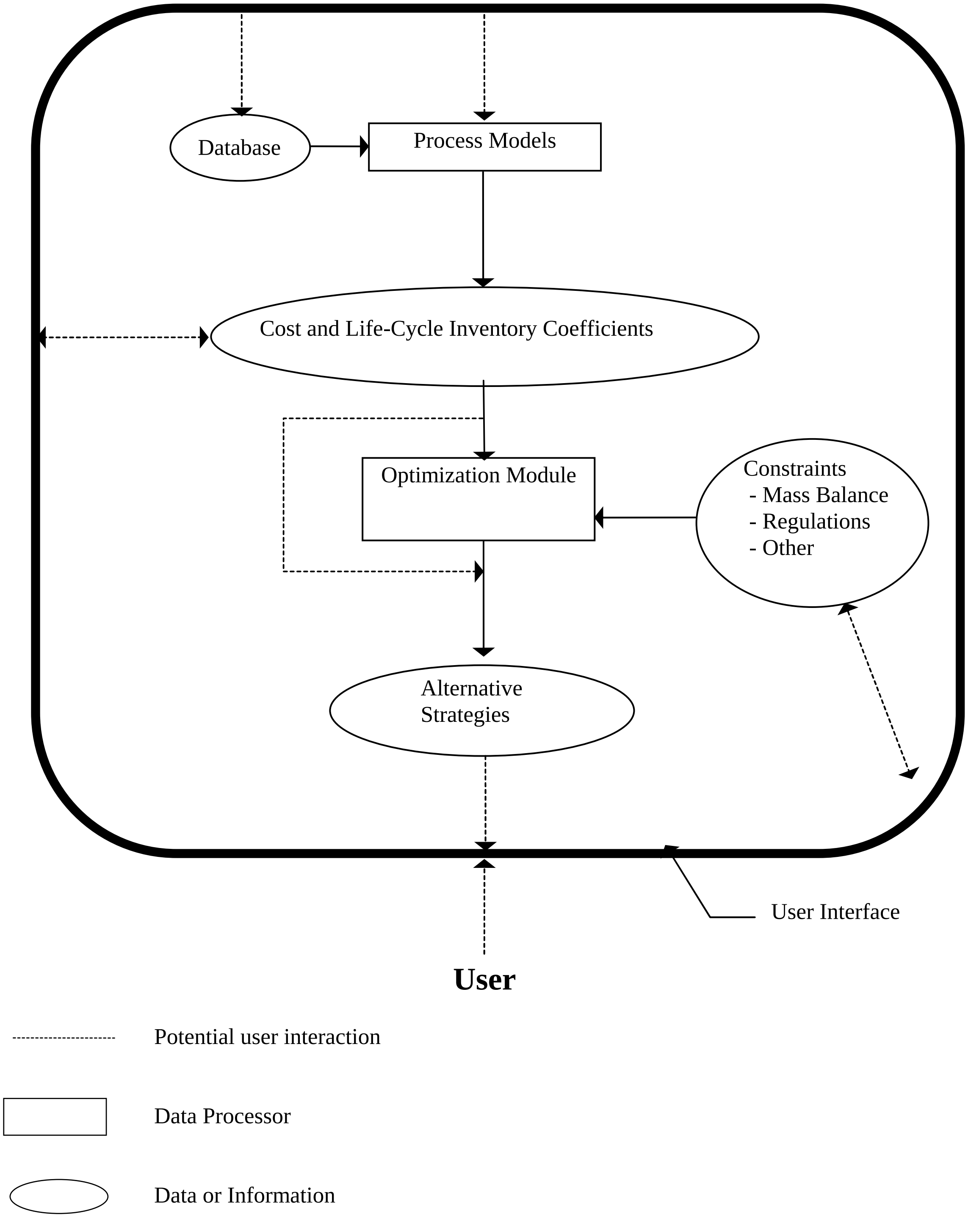


Figure 2-2 Relationship Between the Decision Support System and the User.

2.2 Remanufacturing Implications

To perform a complete life cycle evaluation of a product, the total energy consumption and emissions related to the product are typically compiled. This includes energy and emissions involved in every process from raw materials mining through final product manufacturing. However, for recycled products, it is difficult to identify the appropriate process path to evaluate and compare the LCI parameters to those associated with the comparable virgin process. This is particularly true for open loop recycling in which the recycled material is not reprocessed into the original material. For example, for health reasons, polyethylene terephthalate (PET) bottles are not typically recycled into new PET bottles [3]. Rather, they are processed into fiber for uses such as insulating fill. Obtaining complete product process LCI data would be critical in a life cycle study to compare life cycle implications across products. For example, a packaging study to compare the life cycle of glass bottles to aluminum cans would need to include all steps in the product manufacturing sequence. However, from a recycling standpoint, the MSW LCI model is interested in the question "on a comparative basis, do the cost and life cycle parameters associated with this material justify recycling?". As such, the life cycle parameters for each recyclable material are required only up to a point in the manufacturing process that is common to both virgin and recycled materials. For the LCI model, data are included for recycled and virgin materials from their origins to some common point in the manufacturing process. For example, the LCI parameters for recycled and virgin aluminum are compared up to the point of ingot production. For the recyclable components not included in the scope of this document, common points in the recycling and virgin manufacturing processes have yet to be identified.

3. Remanufacturing Process Model Design

3.1 Introduction

In considering the LCI implications of remanufacturing, a ‘cradle to grave’ approach has not been taken because of the large number of products that can be developed from recycled materials. This makes it difficult to compare emissions from virgin materials production to those associated with recycled materials. For example, newsprint can be recycled into a number of new products including newsprint and egg cartons. It is difficult to make valid LCI comparisons across products of this type when many different manufacturing processes are involved, each with its own environmental load and energy consumption. Therefore, the approach that has been taken is ‘cradle to product’ in which the LCI parameters for virgin and recycled products are compared up to some point in each manufacturing process where a common product can be identified. For aluminum, this is the point at which aluminum ingots are produced. For newsprint and corrugated boxes, this is the point at which newsprint and corrugated box board are produced, respectively. Beyond these common points in the manufacturing process, the LCI parameters for each product will be the same regardless of what product is ultimately manufactured. Downstream LCI implications of items such as staples for constructing corrugated boxes and emissions resulting from transporting the product to the end user, are not included since the LCI implications of these items are the same whether the material is virgin or remanufactured. This distinction is important in that it allows only comparative LCI studies to be performed. An LCI model solution can be obtained that minimizes a selected LCI parameter among the various unit operations, but the absolute environmental load imposed will not include these downstream effects.

For discussion purposes, the tables in this section represent only aluminum ingot manufacturing. Identical tables for newsprint and corrugated boxes are included in Appendix A.

Virgin and recycled material flow diagrams for the three materials discussed are included in reference 2.

3.2 Process Model Data and Calculations

3.2.1 Material Resource Energy

Material resource energy is defined as fuel used in the production of the product other than for electric and steam production or fuel that is physically integrated into the product. Examples of this type of fuel usage are the use of coal to produce coke, which is then used in the manufacture of aluminum, and petroleum products incorporated into plastics [2]. **Error! Not a valid link.** shows these material consumptions and their associated energy consumptions for virgin and recycled aluminum [2]. Similar tables for corrugated boxes and newsprint are shown in Appendix A, Tables 1 and 2, respectively.

Table 3-1 Aluminum Ingot Material Resource Energy

Aluminum Material Resource Energy Per Ton of Ingot Produced							
Virgin Materials				Recycled Materials			
Fuel Type	Default Value	Units	Energy (btu)	Fuel Type	Default Value	Units	Energy (btu)
Natural Gas	0	ft^3	0	Natural Gas	0	ft^3	0
Coal	151	lbm	1,570,400	Coal	0	lbm	0
Petroleum	706	lbm	13,663,218	Petroleum	0	lbm	0
		TOTAL	15,233,618			TOTAL	0

The factors used to convert from the quantity of a fuel consumed to the equivalent energy consumed were slightly inconsistent between references 1 and 2. To ensure consistency between the electric energy process model and the remanufacturing process model (as well as all other modules in the LCI model) the energy conversion factors from reference 1 were used. Only when an energy conversion factor was not included in reference 1 was the factor from reference 2 used. These conversion factors are shown in Table 3-2. These same factors were used for all energy calculations discussed in the following sections.

Table 3-2 Fuel Energy Content

Fuel Type	Energy Content (Btu/Fuel unit)
Coal (lb)	10,400
Natural Gas (cuft)	1,020
Residual Oil (gal.)	150,000
Distillate Oil (gal.)	139,000
Uranium (lb)	985,321,000
Wood (lb)	8,600
Gasoline (gal.)	150,800
Diesel (gal.)	137,000
LPG (gal.)	95,500
Petroleum (lb)	19,353

3.2.2 Combustion Process Energy

Combustion process energy reflects the electricity consumed in producing the product as well as the energy associated with fuel combusted as a part of the production process. Examples of this type of fuel combustion would be the use of coal in process boilers to produce process steam. Table 3-3 shows these fuel consumptions and their associated energy consumptions for virgin and recycled aluminum [2]. Similar tables for corrugated boxes and newsprint are shown in Appendix A, Tables 5 and 6, respectively.

Table 3-3 Aluminum Ingot Combustion Process Energy

Aluminum Combustion Process Energy Per Ton of Ingot Produced							
Virgin Materials				Recycled Materials			
Fuel Type	Default Value	Units	Energy (btu)	Fuel Type	Default Value	Units	Energy (btu)
Electricity	16,545.000	kwh	172,306,086	Electricity	202.000	kwh	2,103,707
Natural Gas	10,889.000	ft^3	11,106,780	Natural Gas	3,550.000	ft^3	3,621,000
LPG	0.170	gal	16,235	LPG		gal	0
Coal	46.100	lbm	479,440	Coal		lbm	0
Distillate Oil	3.180	gal	442,020	Distillate Oil		gal	0
Residual Oil	10.400	gal	1,560,000	Residual Oil	1.380	gal	207,000
Gasoline	0.074	gal	11,159	Gasoline		gal	0
Diesel	2.990	gal	409,630	Diesel		gal	0
Wood	0.000	lbm	0	Wood	0.000	lbm	0
		TOTAL	186,331,350			TOTAL	5,931,707

The remanufacturing data provided by Franklin Associates for aluminum production [2] include an electrical energy biasing concept. This electrical energy bias is based on the concept that the electrical energy for aluminum manufacturing is only 69% derived from the national grid with the remaining 31% being self-generated. Of the 31% self generation, 62 percent was reported as hydro-electric generation for a net hydro-electric bias of approximately 19%. This electrical generation bias is based on the influence that aluminum production has had on the development of hydro-electric generation [2]. Because of the essentially nonexistent LCI impact of hydro-electric power, and the possibility that this bias is not applicable to recycled aluminum, this bias is potentially controversial.

This electrical energy biasing concept was not applied by Franklin Associates to the data for corrugated boxes and newsprint. Rather, the fuels used for self generation were aggregated with those used for process steam production such that it was not possible to implement a user override capability for the assumed self-generation energy production or the fuel mixture utilized [2]. This represents a potential weakness in the flexibility of the remanufacturing process model.

3.2.3 Pre-combustion Process Energy

Pre-combustion process energy reflects the energy consumed in mining and transportation steps required to provide the fuels discussed in Section 3.2.2 in a useable form. Table **Error! Not a valid link.** shows these fuel consumptions and their related energy consumptions for virgin and remanufactured aluminum [2]. Similar tables for corrugated boxes and newsprint are shown in Appendix A, Tables 3 and 4, respectively.

Table 3-4 Aluminum Ingot Pre-combustion Process Energy

Aluminum Pre-combustion Process Energy Per Ton of Ingot Produced

Virgin Materials				Recycled Materials			
Fuel Type	Default Value	Units	Energy (btu)	Fuel Type	Default Value	Units	Energy (btu)
Natural Gas	2480.000	ft^3	2,529,600	Natural Gas	302.000	ft^3	308,040
LPG	0.047	gal	4,489	LPG	0.003	gal	267
Coal	75.400	lbm	784,160	Coal	3.640	lbm	37,856
Distillate Oil	5.000	gal	695,000	Distillate Oil	0.190	gal	26,410
Residual Oil	1.770	gal	265,500	Residual Oil	0.130	gal	19,500
Gasoline	0.250	gal	37,700	Gasoline	0.022	gal	3,318
Nuclear	0.000	lbm	305,450	Nuclear	0.000	lbm	14,780
Hydro Power	37.700	10^3 btu	37,700	Hydro Power	1.850	10^3 btu	1,850
Other	25.000	10^3 btu	25,000	Other	1.220	10^3 btu	1,220
		TOTAL	4,684,598			TOTAL	413,241

3.2.4 Combustion Transportation Energy

Combustion transportation energy represents the energy consumed to transport the various intermediate products to their next manufacturing process location [2]. These data are based on Franklin Associates proprietary data bases that include national average transportation distances and transportation modes (truck, ocean freighter, etc.) for the intermediate materials in the manufacturing steps for the three materials discussed in this document. These transportation energy consumptions as well as the pre-combustion energy consumption and related emissions discussed in Sections 3.2.5 and 3.2.6 , respectively, do not include energy consumption or emissions related to collection or MRF activities associated with recycling these materials. The LCI parameters for these activities are addressed by the collection and MRF process models respectively. Table 3-5 shows the combustion transportation fuel and energy consumption for virgin and recycled aluminum [2]. Similar tables for corrugated boxes and newsprint are shown in Appendix A, Tables 9 and 10, respectively.

Table 3-5 Aluminum Ingot Combustion Transportation Energy

Aluminum Combustion Transportation Energy Per Ton of Ingot Produced							
Virgin Materials				Recycled Materials			
Fuel Type	Default Value	Units	Energy (btu)	Fuel Type	Default Value	Units	Energy (btu)
Combination truck diesel	0.3200	gal	43,840	Combination truck diesel	2.5000	gal	342,500
Rail diesel	4.4600	gal	611,020	Rail diesel	0.0730	gal	10,001
Barge Diesel	0.0520	gal	7,124	Barge Diesel		gal	0
Barge Residual Oil	0.0160	gal	2,400	Barge Residual Oil		gal	0
Ocean Freighter Diesel	2.0300	gal	278,110	Ocean Freighter Diesel		gal	0
Ocean Freighter Residual Oil	20.3000	gal	3,045,000	Ocean Freighter Residual Oil		gal	0
Natural Gas		cu ft	0	Natural Gas		cu ft	0
Electricity	2.1800	kwh	22,703	Electricity		kwh	0
		TOTAL	4,010,197			TOTAL	352,501

3.2.5 Pre-combustion Transportation Energy

As with the combustion process energy discussed in Section 3.2.2, there are pre-combustion energy consumptions associated with the use of fuels for transportation. Table 3-6 shows the pre-combustion transportation fuel usage and energy consumption for virgin and recycled aluminum [2]. Similar tables for corrugated boxes and newsprint are shown in Appendix A, Tables 7 and 8, respectively.

Table 3-6 Aluminum Ingot Pre-combustion Transportation Energy

Aluminum Pre-combustion Transportation Energy Per Ton of Ingot Produced							
Virgin Materials				Recycled Materials			
Fuel Type	Default Value	Units	Energy (btu)	Fuel Type	Default Value	Units	Energy (btu)
Natural Gas	277.000	ft^3	282,540	Natural Gas	24.800	ft^3	25,296
LPG	0.037	gal	3,534	LPG	0.003	gal	315
Coal	3.780	lbm	39,312	Coal	0.340	lbm	3,536
Distillate Oil	0.130	gal	18,070	Distillate Oil	0.011	gal	1,529
Residual Oil	0.780	gal	117,000	Residual Oil	0.069	gal	10,350
Gasoline	0.022	gal	3,318	Gasoline	0.002	gal	302
Nuclear	0.000	lbm	15,765	Nuclear	0.000	lbm	1,379
Hydro Power	1.940	10^3 btu	1,940	Hydro Power	0.170	10^3 btu	170
Other	1.290	10^3 btu	1,290	Other	0.110	10^3 btu	110
		TOTAL	482,768			TOTAL	42,987

3.2.6 Manufacturing Emissions

Tables **Error! Not a valid link.** and **Error! Not a valid link.** show the total emissions associated with aluminum ingot manufacture from virgin and recycled materials, respectively. These emissions include those associated with both the production process and transportation energy consumption. Similar tables for virgin and recycled manufacturing of corrugated boxes and newsprint are shown in Appendix A, Tables 13 and 14 and Tables 15 and 16, respectively. Emission savings for aluminum ingot manufacture from recycled materials over those from virgin manufacture are shown in Table **Error! Not a valid link.**. The recycled versus virgin manufacturing emissions savings for corrugated boxes and newsprint are shown in Appendix A, Tables 14 and 16 and , respectively.

The data from reference 2 provided the emissions related to the manufacture of one ton of intermediate product from virgin and recycled materials for each of the three recyclables. The second to last column in Table **Error! Not a valid link.** and Appendix A, Tables 14 and 16 reflects the net savings for each emission when a ton of the remanufactured material is produced from recycled materials. The product is ingot in the case of aluminum and new corrugated box board and new newsprint for old corrugated boxes and old newsprint, respectively. However, these numbers are in terms of pounds of emissions per ton of comparable product and as such would not be useable as coefficients in an optimization model. In order for these numbers to be used as model coefficients, it is necessary to normalize these values to the recyclable input mass flow required for each ton of material produced. These input mass values are 1,968 pounds recycled OCC per 2000 pounds of new corrugated boxes, 2,344 pounds recycled ONP per 2000 pounds of new newsprint, and 2,141 pounds recycled ACAN per 2000 pounds of new aluminum ingot [2]. The aluminum and newsprint ratios are greater than unity because of material losses during the remanufacturing process while the corrugated box ratio is less than unity because of the fact that OCC remanufacturing consists of simply re-pulping the recycled product and adding 32 pounds of starch adhesive per ton of final product [2].

These material ratios are multiplied by the second to last column in each of the three subject tables to arrive at the net emissions savings for each emission type in terms of pounds of emissions per ton of recycled material flowing to the remanufacturing process. These emissions savings are shown in the last column of each of the three subject tables.

Table 3-7 Virgin Aluminum Ingot Manufacturing Emissions

Aluminum Emissions Per Ton of Ingot Produced		Virgin Material Emissions (lbm/ton)			
Emission Type	Variable Names	Default Process Related	Default Fuel Related	Based on Default National Generation	Based on Actual National Generation
Atmospheric Emissions	al_table	V_al_P	V_al_F	V_al_B	V_al_A
Particulates (PM10)	al a pm 10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Particulates (Total)	al a pm	7.77E+01	2.61E+01	4.34E+01	4.34E+01
Nitrogen Oxides	al a no	8.60E-01	7.60E+01	1.13E+02	1.13E+02
Hydrocarbons (non CH4)	al a hc	6.11E+00	4.51E+01	3.19E+01	3.19E+01
Sulfur Oxides	al a so	3.22E+01	1.33E+02	2.26E+02	2.26E+02
Carbon Monoxide	al a co	1.97E+02	1.84E+01	3.72E+01	3.72E+01
CO2 (biomass)	al a co2 bm	0.00E+00	0.00E+00	8.60E+01	8.60E+01
CO2 (non biomass)	al a co2	2.97E+03	1.84E+04	2.59E+04	2.59E+04
Ammonia	al a nh4	2.00E-02	2.40E-03	1.65E-03	1.65E-03
Lead	al a pb	9.80E-07	3.90E-03	4.60E-07	4.60E-07
Methane	al a ch4	0.00E+00	1.30E-01	1.62E-01	1.62E-01
Hydrochloric acid	al a hcl	1.10E-04	7.00E-05	4.98E-05	4.98E-05
Solid Waste					
Ash	al sw 1	0.00E+00	1.79E+03	3.15E+03	3.15E+03
Sludge	al sw 2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Scrap	al sw 3	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other	al sw 4	2.25E+02	0.00E+00	0.00E+00	0.00E+00
Red Mud	al sw 5	3.18E+03	0.00E+00	0.00E+00	0.00E+00
Waterborne Emissions					
Dissolved Solids	al w ds	9.88E+00	4.30E-01	4.40E+00	4.40E+00
Suspended Solids	al w ss	4.13E+01	5.90E-03	3.88E-03	3.88E-03
BOD	al w bod	2.45E+00	6.40E-03	4.24E-03	4.24E-03
COD	al w cod	3.64E+01	3.00E-02	2.12E-02	2.12E-02
Oil	al w oil	7.30E-01	4.50E-02	8.40E-02	8.40E-02
Sulfuric Acid	al w h2so4	0.00E+00	1.11E+01	1.90E+01	1.90E+01
Iron	al w fe	1.10E-01	2.78E+00	4.72E+00	4.72E+00
Ammonia	al w nh4	2.10E-01	8.30E-04	5.78E-04	5.78E-04
Copper	al w cu	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cadmium	al w cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Arsenic	al w as	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mercury	al w hg	2.30E-07	0.00E+00	0.00E+00	0.00E+00
Phosphate	al w po4	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Selenium	al w se	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chromium	al w cr	3.10E-06	2.10E-06	7.08E-07	7.08E-07
Lead	al w pb	1.50E-06	9.20E-07	6.19E-07	6.19E-07
Zinc	al w zn	2.00E-05	1.30E-05	9.22E-06	9.22E-06

Table 3-8 Recycled Aluminum Ingot Manufacturing Emissions

Aluminum Emissions Per Ton of Ingot Produced		Recycled Material Emissions (lbm/ton)				Emission Savings (lbm/ton new material)	Emission Savings (lbm/ton ACAN)
Emission Type	Variable Names	Default Process Related	Default Fuel Related	Based on Default National Generation	Based on Actual National Generation	(V_AL_P+V_AL_F-V_AL_B+V_AL_A)-(R_AL_P+R_AL_F-R_AL_B+R_AL_A)	(2000/NET_AL/AL_PER_TON_MATERIAL)
Atmc 0	al_table	R_al_P	R_al_F	R_al_B	R_al_A	NET_al	SAV_al
Particulates (PM10)	al a pm 10	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Particulates (Total)	al a pm	4.00E-01	5.90E-01	5.29E-01	5.29E-01	1.03E+ 02	9.60E+ 01
Nitrogen Oxides	al a no	0.00E+ 00	2.49E+ 00	1.39E+ 00	1.39E+ 00	7.44E+ 01	6.95E+ 01
Hydrocarbons (non CH4)	al a hc	0.00E+ 00	5.81E+ 00	3.89E-01	3.89E-01	4.54E+ 01	4.24E+ 01
Sulfur Oxides	al a so	0.00E+ 00	2.99E+ 00	2.75E+ 00	2.75E+ 00	1.62E+ 02	1.52E+ 02
Carbon Monoxide	al a co	0.00E+ 00	1.07E+ 00	4.54E-01	4.54E-01	2.14E+ 02	2.00E+ 02
CO2 (biomass)	al a co2 bm	0.00E+ 00	0.00E+ 00	1.05E+ 00	1.05E+ 00	0.00E+ 00	0.00E+ 00
CO2 (non biomass)	al a co2	0.00E+ 00	8.86E+ 02	3.16E+ 02	3.16E+ 02	2.05E+ 04	1.92E+ 04
Ammonia	al a nh4	0.00E+ 00	1.80E-04	2.02E-05	2.02E-05	2.22E-02	2.08E-02
Lead	al a pb	0.00E+ 00	8.60E-05	5.62E-09	5.62E-09	3.81E-03	3.56E-03
Methane	al a ch4	0.00E+ 00	1.30E-02	1.98E-03	1.98E-03	1.17E-01	1.09E-01
Hydrochloric acid	al a hcl	0.00E+ 00	5.30E-06	6.08E-07	6.08E-07	1.75E-04	1.63E-04
Solid Waste							
Ash	al sw 1	0.00E+ 00	3.49E+ 01	3.85E+ 01	3.85E+ 01	1.75E+ 03	1.64E+ 03
Sludge	al sw 2	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Scrap	al sw 3	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Other	al sw 4	2.36E+ 01	0.00E+ 00	0.00E+ 00	0.00E+ 00	2.01E+ 02	1.88E+ 02
Red Mud	al sw 5	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	3.18E+ 03	2.97E+ 03
Waterborne Emissions							
Dissolved Solids	al w ds	0.00E+ 00	3.20E-02	5.37E-02	5.37E-02	1.03E+ 01	9.60E+ 00
Suspended Solids	al w ss	1.00E+ 00	4.40E-04	4.74E-05	4.74E-05	4.03E+ 01	3.77E+ 01
BOD	al w bod	0.00E+ 00	4.80E-04	5.18E-05	5.18E-05	2.46E+ 00	2.29E+ 00
COD	al w cod	0.00E+ 00	2.20E-03	2.59E-04	2.59E-04	3.64E+ 01	3.40E+ 01
Oil	al w oil	0.00E+ 00	5.00E-03	1.03E-03	1.03E-03	7.70E-01	7.19E-01
Sulfuric Acid	al w h2so4	0.00E+ 00	2.10E-01	2.32E-01	2.32E-01	1.09E+ 01	1.02E+ 01
Iron	al w fe	0.00E+ 00	5.30E-02	5.77E-02	5.77E-02	2.84E+ 00	2.65E+ 00
Ammonia	al w nh4	0.00E+ 00	6.20E-05	7.05E-06	7.05E-06	2.11E-01	1.97E-01
Copper	al w cu	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Cadmium	al w cd	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Arsenic	al w as	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Mercury	al w hg	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	2.30E-07	2.15E-07
Phosphate	al w po4	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Selenium	al w se	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00	0.00E+ 00
Chromium	al w cr	0.00E+ 00	1.50E-07	8.64E-09	8.64E-09	5.05E-06	4.72E-06
Lead	al w pb	0.00E+ 00	6.90E-08	7.56E-09	7.56E-09	2.35E-06	2.20E-06
Zinc	al w zn	0.00E+ 00	1.00E-06	1.13E-07	1.13E-07	3.20E-05	2.99E-05

3.2.7 Manufacturing Energy Consumption

The total energy for aluminum ingot manufacture from virgin and recycled materials is shown in Table **Error! Not a valid link.**. This table includes the savings for recycled versus virgin manufacture. As with manufacturing emissions discussed in Section 3.2.6, these energy savings have been normalized to a per ton of recycled aluminum cans basis to allow their use as LCI model coefficients. Similar tables for corrugated boxes and newsprint are shown in Appendix A, Tables 11 and 12, respectively.

Table 3-9 Aluminum Ingot Energy Usage

Aluminum Energy Usage Per Ton of Ingot Produced		Virgin Material Energy Usage (btu/ton)	Recycled Material Energy Usage (btu/ton)	Energy Savings (btu/ton new material)	Energy Savings (btu/ton ACAN)
	Variable Names				
Energy Type	al_energy_table	al_V_ENG	al_R_ENG	NET_ACAN_ENG SAV	ACAN_ENG_S AV
Material Resource	al_mr_eng	15,233,618	0	15,233,618	14,230,376
Process	al_p_eng	186,331,350	5,931,707	180,399,643	168,519,050
Pre-combustion Process	al_p_pc_eng	4,684,598	413,241	4,271,357	3,990,058
Transportation	al_t_eng	4,010,197	352,501	3,657,696	3,416,811
Pre-Combustion Trans.	al_t_pc_eng	482,768	42,987	439,781	410,818
Total	al_tot_eng	210,742,532	6,740,436	204,002,096	190,567,114

3.3 Remanufacturing Summary

The default values and calculation methodology discussed in the preceding sections have been implemented in the remanufacturing portion of the overall LCI model to ensure that the LCI implications of virgin versus recycled materials are accounted for. The intent of this implementation is to provide a model based on the best available default information while being responsive to user input override values for these defaults.

4. References

1. Franklin Associates, Ltd. (1995), Unpublished Electric Energy Data, Submitted to Research Triangle Institute.
2. Franklin Associates, Ltd., Unpublished Remanufacturing Data, Submitted to Research Triangle Institute.
3. Tchobanoglous, G., Theisen, H., and Vigil, S., Integrated Solid Waste Management, McGraw-Hill, Inc., New York, 1993.

APPENDICES