



**Determination of the Impact of
Waste Management Activities on
Greenhouse Gas Emissions:
2005 Update
Final Report
Contract No. K2216-04-0006**

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Table of Contents

EXECUTIVE SUMMARY.....	1
1 INTRODUCTION.....	5
2 METHODOLOGY	11
2.1 INPUTS AND BASELINES FOR THE STREAMLINED LIFE-CYCLE INVENTORY.....	11
2.2 HOW THESE INPUTS ARE TALLIED AND COMPARED	13
2.2.1 GHG EMISSIONS AND CARBON SINKS ASSOCIATED WITH RAW MATERIALS ACQUISITION AND MANUFACTURING/FABRICATION	15
2.2.2 GHG EMISSIONS AND CARBON SINKS ASSOCIATED WITH WASTE MANAGEMENT.....	25
2.3 ACCOUNTING ISSUES.....	28
2.3.1 LANDFILL GAS – METHANE COMMITMENT VS. WASTE-IN-PLACE METHODS.....	28
2.3.2 CARBON SINKS.....	28
2.3.3 TRANSBOUNDARY FLOW OF MATERIALS	29
3 METALS & GLASS	31
3.1 ALUMINUM.....	31
3.1.1 RECYCLING	34
3.1.2 LIMITATIONS	36
3.2 STEEL	36
3.2.1 RECYCLING	38
3.2.2 COMBUSTION	40
3.2.3 LIMITATIONS	40
3.3 COPPER WIRE.....	40
3.3.1 RECYCLING	42
3.3.2 COMBUSTION	43
3.3.3 LIMITATIONS	44
3.4 GLASS.....	44
3.4.1 RECYCLING	45
3.4.2 COMBUSTION	47
3.4.3 LIMITATIONS	47
4 PLASTICS & TIRES.....	49
4.1 HDPE, PET, AND OTHER PLASTIC PACKAGING.....	49
4.1.1 RECYCLING	50
4.1.2 COMBUSTION	52
4.1.3 LIMITATIONS	52
4.2 TIRES.....	53
4.2.1 RECYCLING	54
4.2.2 COMBUSTION	56
4.2.3 LIMITATIONS	56
5 FOREST PRODUCTS.....	59
5.1 NEWSPRINT, FINE PAPER, CARDBOARD, OTHER PAPER	59
5.1.1 RECYCLING	61
5.1.2 ANAEROBIC DIGESTION.....	64
5.1.3 COMBUSTION	67
5.1.4 LANDFILLING	68

5.1.5	LIMITATIONS	71
6	ORGANICS.....	73
6.1	FOOD SCRAPS AND YARD TRIMMINGS.....	73
6.1.1	COMPOSTING.....	73
6.1.2	ANAEROBIC DIGESTION.....	76
6.1.3	COMBUSTION	77
6.1.4	LANDFILLING	77
6.1.5	LIMITATIONS	78
7	ELECTRONICS AND WHITE GOODS.....	79
7.1	ELECTRONICS	79
7.1.1	RECYCLING	81
7.1.2	COMBUSTION	82
7.1.3	LIMITATIONS	83
7.2	WHITE GOODS	83
7.2.1	RECYCLING	84
7.2.2	COMBUSTION	85
7.2.3	LIMITATIONS	86
8	EMISSION FACTOR OVERVIEW	87
9	REFERENCES.....	97
10	GLOSSARY.....	101
APPENDIX A. PROVINCIAL ELECTRICITY GENERATION		103
1	PROVINCIAL AND NATIONAL AVERAGE ELECTRICITY COEFFICIENTS	105
1.1	KEY DATA SOURCES AND ASSUMPTIONS.....	105
1.2	BACKGROUND AND METHOD.....	106
1.3	GENERAL METHOD USED TO PRODUCE END USE EMISSION FACTORS FOR ELECTRICITY	106
1.4	PRE-COMBUSTION ADDERS	107
1.4.1	PETROLEUM AND NATURAL GAS.....	108
1.4.2	COAL.....	108
1.5	PROVINCE-SPECIFIC NOTES	109
2	PRODUCTION-WEIGHTED ELECTRICITY COEFFICIENTS.....	110
2.1	KEY DATA SOURCES AND ASSUMPTIONS.....	110
2.2	BACKGROUND AND METHOD.....	114
3	TRANSBOUNDARY EFFECTS: U.S. ELECTRICITY FACTORS.....	114
3.1	KEY DATA SOURCES AND ASSUMPTIONS.....	114
3.2	BACKGROUND AND METHOD.....	115
4	MARGINAL ELECTRICITY COEFFICIENT	115
APPENDIX B. BACKGROUND TABLES.....		117

List of Exhibits

EXHIBIT ES- 1 WASTE MATERIAL TYPES EXAMINED.	3
EXHIBIT 2-1. COMPONENTS OF NET EMISSIONS FOR VARIOUS WASTE MANAGEMENT OPTIONS	15
EXHIBIT 2-2. EMISSION FACTORS FOR FUEL COMBUSTION. SOURCE: EC 2002	18
EXHIBIT 2-3. EMISSION FACTORS FOR END USE ELECTRICITY	19
EXHIBIT 2-4. MASS BALANCE APPROACH FOR FOREST CARBON SINK	24
EXHIBIT 3-1. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS FOR ALUMINUM (TONNES ECO₂/TONNE)	33
EXHIBIT 3-2. RECYCLING EMISSIONS FOR ALUMINUM (TONNES ECO₂/TONNE)	34
EXHIBIT 3-3. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS FOR STEEL (TONNES ECO₂/TONNE)	38
EXHIBIT 3-4. RECYCLING EMISSIONS FOR STEEL (TONNES ECO₂/TONNE)	38
EXHIBIT 3-5. COMBUSTION EMISSIONS FOR STEEL (TONNES ECO₂/TONNE)	40
EXHIBIT 3-6. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS FOR COPPER WIRE (TONNES ECO₂/TONNE)	42
EXHIBIT 3-7. RECYCLING EMISSIONS FOR COPPER WIRE (TONNES ECO₂/TONNE)	42
EXHIBIT 3-8. COMBUSTION EMISSIONS FOR COPPER (TONNES ECO₂/TONNE)	44
EXHIBIT 3-9. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS FOR GLASS (TONNES ECO₂/TONNE)	45
EXHIBIT 3-10. RECYCLING EMISSIONS FOR GLASS (TONNES ECO₂/TONNE)	45
EXHIBIT 3-11. COMBUSTION EMISSIONS FOR GLASS (TONNES ECO₂/TONNE)	47
EXHIBIT 4-1. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS FOR HDPE, PET, OTHER PLASTICS, AND TIRES (TONNES ECO₂/TONNE)	50
EXHIBIT 4-2. RECYCLING EMISSIONS FOR HDPE, PET, AND OTHER PLASTIC (TONNES ECO₂/TONNE)	50
EXHIBIT 4-3. COMBUSTION EMISSIONS FOR HDPE, PET, AND OTHER PLASTIC (TONNES ECO₂/TONNE)	52
EXHIBIT 4-4. ANNUAL SCRAP TIRE USAGE BY PROVINCE	54
EXHIBIT 4-5. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS FOR TIRES (TONNES ECO₂/TONNE)	54
EXHIBIT 4-6. RECYCLING EMISSIONS FOR TIRES (TONNES ECO₂/TONNE)	55
EXHIBIT 4-7. COMBUSTION EMISSIONS FOR TIRES IN CEMENT KILNS (TONNES ECO₂/TONNE)	56
EXHIBIT 5-1. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS FOR NEWSPRINT, FINE PAPER, CARDBOARD, AND OTHER PAPER (TONNES ECO₂/TONNE)	59
EXHIBIT 5-2. RECYCLING EMISSIONS FOR NEWSPRINT, FINE PAPER, CARDBOARD, AND OTHER PAPER (TONNES ECO₂/TONNE)	61
EXHIBIT 5-3. FOREST PRODUCT SECONDARY PRODUCT DISTRIBUTION	63

EXHIBIT 5-4 ANAEROBIC DIGESTION EMISSIONS FOR NEWSPRINT, FINE PAPER, CARDBOARD, AND OTHER PAPER (TONNES ECO₂/TONNE)	67
EXHIBIT 5-5 COMBUSTION EMISSIONS FOR NEWSPRINT, FINE PAPER, CARDBOARD, AND OTHER PAPER (TONNES ECO₂/TONNE)	68
EXHIBIT 5-6. DEFINITION OF OTHER PAPER	69
EXHIBIT 5-7 LANDFILLING EMISSIONS FOR NEWSPRINT, FINE PAPER, CARDBOARD, AND OTHER PAPER (TONNES ECO₂/TONNE)	71
EXHIBIT 6-1. GHG EMISSIONS FROM MSW MANAGEMENT OPTIONS FOR YARD TRIMMINGS AND FOOD SCRAPS (TONNES ECO₂/TONNE)	73
EXHIBIT 6-2 CENTRALIZED COMPOSTING EMISSIONS FOR FOOD SCRAPS AND YARD TRIMMINGS (TONNES ECO₂/TONNE)	74
EXHIBIT 6-3 NET GHG EMISSIONS FOR COMPOSTING CALCULATIONS	76
EXHIBIT 6-4 ANAEROBIC DIGESTION EMISSIONS FOR FOOD SCRAPS AND YARD TRIMMINGS (TONNES ECO₂/TONNE)	77
EXHIBIT 6-5 COMBUSTION EMISSIONS FOR FOOD SCRAPS AND YARD TRIMMINGS (TONNES ECO₂/TONNE)	77
EXHIBIT 6-6 LANDFILL EMISSIONS FOR FOOD SCRAPS AND YARD TRIMMINGS (TONNES ECO₂/TONNE)	78
EXHIBIT 7-1. PERCENT MATERIAL COMPOSITION OF FOUR ELECTRONIC DEVICES	80
EXHIBIT 7-2. GHG EMISSIONS FROM MSW MANAGEMENT OPTIONS FOR ELECTRONICS (TONNES ECO₂/TONNE)	81
EXHIBIT 7-3 RECYCLING EMISSIONS FOR PERSONAL COMPUTERS, TELEVISIONS, MICROWAVES, AND VCERS (TONNES ECO₂/TONNE)	81
EXHIBIT 7-4 SECONDARY MATERIALS PRODUCED FROM RECYCLED ELECTRONICS	82
EXHIBIT 7-5 COMBUSTION EMISSIONS FOR PERSONAL COMPUTERS, TELEVISIONS, MICROWAVES, AND VCERS (TONNES ECO₂/TONNE)	83
EXHIBIT 7-6 RAW MATERIAL COMPOSITION OF CANADIAN WHITE GOODS	84
EXHIBIT 7-7. GHG EMISSIONS FROM MSW MANAGEMENT OPTIONS FOR WHITE GOODS (TONNES ECO₂/TONNE)	84
EXHIBIT 7-8 RECYCLING EMISSIONS FOR WHITE GOODS (TONNES ECO₂/TONNE)	85
EXHIBIT 7-9 COMBUSTION EMISSIONS FOR WHITE GOODS (TONNES ECO₂/TONNE)	86
EXHIBIT 8-1. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS, WITH CARBON SINKS (TONNES ECO₂/TONNE)	88
EXHIBIT 8-2. GHG EMISSIONS FROM WASTE MANAGEMENT OPTIONS, EXCLUDING CARBON SINKS (TONNES ECO₂/TONNE)	89
EXHIBIT 8-3. GHG EMISSIONS FROM MSW MANAGEMENT OPTIONS COMPARED TO LANDFILLING* (OPTION'S NET EMISSIONS MINUS LANDFILLING NET EMISSIONS), INCLUDING CARBON SINKS (TONNES ECO₂/TONNE)	91
EXHIBIT 8-4. GHG EMISSIONS FROM MSW MANAGEMENT OPTIONS COMPARED TO LANDFILLING* (OPTION'S NET EMISSIONS MINUS LANDFILLING NET EMISSIONS), EXCLUDING CARBON SINKS (TONNES ECO₂/TONNE)	92
EXHIBIT 8-5. ENERGY IMPACTS FROM MSW MANAGEMENT OPTIONS (GJ/TONNE)	95

EXHIBIT 8-6. ENERGY IMPACTS FROM MSW MANAGEMENT OPTIONS COMPARED TO LANDFILLING* (OPTION'S NET EMISSIONS MINUS LANDFILLING NET EMISSIONS) (GJ/TONNE)	96
EXHIBIT A-1. 2003 GHG ELECTRICITY EMISSION FACTORS (G ECO₂ / KWH)	105
EXHIBIT A-2. PRODUCTION DISTRIBUTION BY PROVINCE	112
EXHIBIT A-3. DERIVATION OF PROVINCIAL PRODUCTION DISTRIBUTION	113
EXHIBIT B-1 2001 GHG EMISSIONS ASSOCIATED WITH THE PRODUCTION, REFINING, AND TRANSPORTATION OF NATURAL GAS	117
EXHIBIT B-2 2001 GHG EMISSIONS ASSOCIATED WITH THE PRODUCTION, REFINING AND TRANSPORTATION OF REFINED PETROLEUM PRODUCTS	118
EXHIBIT B-3. CANADIAN PRODUCTION OF NATURAL GAS AND REFINED PETROLEUM PRODUCTS IN 2001¹	119
EXHIBIT B-4 RETENTION RATES OF VARIOUS MATERIALS	120
EXHIBIT B-5 CURRENT MIX VALUES FOR VARIOUS MATERIAL TYPES	120
EXHIBIT B-6 ENERGY USE FOR VIRGIN PRODUCTION OF ROLLED ALUMINUM	121
EXHIBIT B-7 ENERGY USE FOR RECYCLED PRODUCTION OF ROLLED ALUMINUM	122
EXHIBIT B-8 ENERGY USE FOR VIRGIN PRODUCTION OF EXTRUDED ALUMINUM	123
EXHIBIT B-9 ENERGY USE FOR RECYCLED PRODUCTION OF EXTRUDED ALUMINUM	124
EXHIBIT B-10 ENERGY USE FOR VIRGIN PRODUCTION OF SHAPE CAST ALUMINUM	125
EXHIBIT B-11 ENERGY USE FOR RECYCLED PRODUCTION OF SHAPE CAST ALUMINUM.	126
EXHIBIT B-12 PFC-ANODE INFORMATION	127
EXHIBIT B-13 ENERGY USE FOR VIRGIN PRODUCTION OF STEEL	127
EXHIBIT B-14 ENERGY USE FOR RECYCLED PRODUCTION OF STEEL	128
EXHIBIT B-15 DERIVATION OF ENERGY PER TONNE ESTIMATES FOR STEEL RAW MATERIALS ACQUISITION.	129
EXHIBIT B-16 ENERGY USE AT MATERIALS RECOVERY FACILITY	129
EXHIBIT B-17 MANUFACTURING ENERGY USE FOR SELECTED MATERIALS, VIRGIN INPUTS	130
EXHIBIT B-18 MANUFACTURING ENERGY FOR SELECTED MATERIALS, FROM RECYCLED INPUTS	131
EXHIBIT B-19 TRANSPORTATION ENERGY USE – VIRGIN	132
EXHIBIT B-20 TRANSPORTATION ENERGY USE - RECYCLED	132
EXHIBIT B-21 TRANSPORTATION ASSOCIATED WITH MANUFACTURING AND FABRICATION	133
EXHIBIT B-22 TRANSPORT TO CONSUMER -- GLASS (USED AS SURROGATE FOR OTHER MATERIALS)	133
EXHIBIT B-23 ENERGY USE FOR VIRGIN PRODUCTION OF COPPER WIRE	134
EXHIBIT B-24 ENERGY USE FOR RECYCLED PRODUCTION OF COPPER WIRE	135
EXHIBIT B-25 ENERGY USE FOR VIRGIN PRODUCTION OF GLASS BOTTLES	135

EXHIBIT B-26 ENERGY USE FOR RECYCLED PRODUCTION OF GLASS BOTTLES	136
EXHIBIT B-27 DERIVATION OF PER-TONNE ENERGY ESTIMATES FOR RAW MATERIALS ACQUISITION OF GLASS¹	137
EXHIBIT B-28 ENERGY USE FOR VIRGIN PRODUCTION OF HDPE	138
EXHIBIT B-29 ENERGY USE FOR RECYCLED PRODUCTION OF HDPE	138
EXHIBIT B-30 ENERGY USE FOR VIRGIN PRODUCTION OF PET	139
EXHIBIT B-31 ENERGY USE FOR RECYCLED PRODUCTION OF PET	139
EXHIBIT B-32 ENERGY USE FOR VIRGIN PRODUCTION OF OTHER PLASTIC (LDPE)	140
EXHIBIT B-33 ENERGY USE FOR RECYCLED PRODUCTION OF OTHER PLASTIC (LDPE)	140
EXHIBIT B-34 HIGH DENSITY POLYETHYLENE	141
EXHIBIT B-35 PET BOTTLE GRADE	141
EXHIBIT B-36 LINEAR LOW DENSITY POLYETHYLENE (OTHER PLASTICS)	142
EXHIBIT B-37 ENERGY USE FOR VIRGIN PRODUCTION OF TIRES	142
EXHIBIT B-38 ENERGY USE FOR RECYCLED PRODUCTION OF TIRES	143
EXHIBIT B-39 ENERGY USE FOR VIRGIN PRODUCTION OF NEWSPRINT	143
EXHIBIT B-40 ENERGY USE FOR RECYCLED PRODUCTION OF NEWSPRINT	144
EXHIBIT B-41 ENERGY USE FOR VIRGIN PRODUCTION OF FINE PAPER	144
EXHIBIT B-42 ENERGY USE FOR RECYCLED PRODUCTION OF FINE PAPER	145
EXHIBIT B-43 ENERGY USE FOR VIRGIN PRODUCTION OF CARDBOARD	145
EXHIBIT B-44 ENERGY USE FOR RECYCLED PRODUCTION OF CARDBOARD	146
EXHIBIT B-45 ENERGY USE FOR VIRGIN PRODUCTION OF “OTHER” PAPER	146
EXHIBIT B-46 ENERGY USE FOR RECYCLED PRODUCTION OF “OTHER” PAPER	147
EXHIBIT B-47 ENERGY USE FOR VIRGIN PRODUCTION OF TISSUE PAPER	147
EXHIBIT B-48 ENERGY USE FOR RECYCLED PRODUCTION OF TISSUE PAPER	148
EXHIBIT B-49 DERIVATION OF PER-TONNE ENERGY ESTIMATES FOR RAW MATERIAL ACQUISITION OF PAPER	149
EXHIBIT B-50 WASTE MANAGEMENT EMISSIONS	150
EXHIBIT B-51 ENERGY USE FOR VIRGIN PRODUCTION OF PLASTIC USED IN ASPHALT	150
EXHIBIT B-52 ENERGY USE FOR RECYCLED PRODUCTION OF PLASTIC USED IN ASPHALT	151
EXHIBIT B-53 ENERGY USE FOR VIRGIN PRODUCTION OF CRT GLASS	152
EXHIBIT B-54 ENERGY USE FOR RECYCLED PRODUCTION OF CRT GLASS	152
EXHIBIT B-55 ENERGY USE FOR VIRGIN PRODUCTION OF CRT GLASS	153
EXHIBIT B-56 ENERGY USE FOR RECYCLED PRODUCTION OF CRT GLASS	153

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Executive Summary

As policy makers seek to reduce greenhouse gas (GHG) emissions, many in Canada and elsewhere have found that waste-related mitigation opportunities are both significant and cost-effective. Several analyses at the local and national scales have suggested that potential reductions are on the same scale as energy efficiency and electricity repowering. To better evaluate these opportunities, GHG emission factors are needed for key materials and waste management options.

The goal of this report is two-fold:

1. To build capacity surrounding municipal solid waste management options in relation to GHG emissions; and
2. To attempt to quantify, from a life-cycle perspective, emission factors associated with Canadian residential as well as industrial, commercial, and institutional (IC&I) solid waste management practices.

The GHG emission factors associated with Canadian residential and industrial, commercial, and institutional (IC&I) waste management practices can be used to inform decision making at all levels of government and in the private sector. These emission factors can help decision makers compare the GHG implications of waste management choices, i.e., they indicate – in general terms – the magnitude of emission reductions or increases.

GHG emission factors in this study only serve as a common basis for comparison. They are not intended for, nor should they be used in GHG inventories or for quantifying emission reduction offsets for the reasons provided below:

- *The assumptions, methods, and parameter values used in this study are not necessarily consistent with GHG inventory methodology or protocols developed for projects;*
- *These emission factors provide only a general indication of GHG implications of waste management choices;*
- *These emission factors do not provide the absolute quantity of emissions or reductions because of uncertainties and simplifying assumptions in the analyses; and*
- *Difficulties with the quantification, monitoring and verification of emissions which occur at dozens of different stages in the life cycle and geographic locations.*

The option that is employed to manage a product or material that has been "used-up" can have impacts on GHG emissions, both directly (e.g., emissions of methane from anaerobic decomposition of disposed organic matter) and indirectly (e.g., recycling aluminum saves energy and eliminates some emissions that would otherwise arise from producing primary aluminum). GHG emission factors – values that represent the net effect on GHG emissions when all direct and indirect impacts are considered over the life cycle of a material – can be used to compare

particular "waste" management options in terms of GHG friendliness. The GHG emission factors that have been developed as a result of this work can be found in Section 8. Sections preceding Section 8 are background information as to how the factors have been developed.

This report represents the culmination of a series of projects to develop and refine life-cycle GHG emission factors for specific materials commonly occurring in the Canadian residential and IC&I waste stream. The original report, "Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions" (ICF 2001) described the net GHG emissions for selected materials, across a partial life cycle, ending with various waste management fates. This report – the "2005 Update" – presents the efforts of previous work and results of research undertaken more recently. The most recent research has included the addition of several materials that are common in the residential and IC&I waste streams and where the potential of alternative waste management options are of interest to Environment Canada and Natural Resources Canada (NRCan): electronics, white goods, copper wire, and tires. In addition, this report reflects efforts to improve the modelling of paper recycling by simulating open loop recycling – i.e., where the second generation products differ from the product being recycled. The emission factors provided in this report also reflect the use of more recent data to calculate emissions from electricity use.

Much of the life-cycle methodology and some of the data employed in this project, and some of the passages in this report, are drawn directly from research performed for the U.S. Environmental Protection Agency, Office of Solid Waste (EPA 2002). This work, conducted since 1993 by ICF Consulting and others, has led to development of GHG emission factors for recycling, composting, combustion, and landfilling, focusing on U.S. conditions. The Canadian emission factors build and expand on this work by (1) utilizing Canadian data wherever possible, (2) including anaerobic digestion (AD) among the waste management options, (3) including several new material types not yet investigated in the United States (e.g., electronics, white goods), (4) disaggregating upstream energy use by life-cycle stage, and (5) characterizing provincial electricity generation fuel mixtures to more accurately reflect the geographic distribution of manufacturing for each of the materials.

The materials examined in this report are presented in Exhibit ES- 1. The waste management options examined include recycling, landfilling, anaerobic digestion, combustion, and composting¹. For each combination of material and waste management option, a net emission factor is developed to characterize the sum of GHG emissions and sinks across a partial life cycle.

¹ The inclusion of recycling and composting as "waste" management activities is based on traditional thinking, whereas the businesses and agencies involved in these activities are increasingly more likely to think of these materials as "resources" that need to be properly managed at the end of their useful life.

Exhibit ES- 1 Waste Material Types Examined

Category	Specific Materials
Metals and glass	Aluminum, steel, copper wire, glass bottles
Plastics and tires	HDPE (high density polyethylene), PET (polyethylene terephthalate), other plastics, tires
Forest Products	Newsprint, fine paper, cardboard, other paper
Organics	Food scraps, yard trimmings
Electronics and white goods	Personal computers, televisions, microwaves, and VCR, white goods

By examining the emission factors presented in this report, one can conclude that:

- In general, recycling reduces GHG emissions relative to landfilling. The emission reductions, per tonne of material, are quite significant in some cases (e.g., aluminum).
- The effect of including or excluding carbon sinks has an important effect on the emission factors for paper, food scraps, and yard trimmings when managed through recycling or landfilling.
- For metals and glass, there is almost no distinction in GHG emissions between any of the “downstream” waste management methods, i.e., landfilling, combustion, anaerobic digestion, and composting.² For the other materials – paper, plastics, organics, electronics, and tires – the choice of management method can have significant implications.

Users of the emission factors presented in this report should be aware that they incorporate many limitations and carry considerable uncertainty. Although the analysis is based on the best available data that could be collected within the time and resource constraints of the project, and the assumptions are believed to be reasonable, the accuracy of the analysis is limited by the use of these assumptions and limitations in the data sources. Despite the uncertainty in the emission factors, they provide a reasonable estimate of the overall GHG impacts associated with waste management options in Canada, and will provide a sound basis for informing waste management

² Steel is an exception because GHGs are reduced when steel is recovered from combustion facilities and subsequently recycled.

decisions and evaluating voluntary actions to reduce GHG emissions in the waste management arena.

1 Introduction

Waste management decisions are becoming increasingly complex for policy makers and waste managers at all levels. The development of new technologies, combined with an increased awareness of the effect of waste management on anthropogenic greenhouse gases (GHGs) that are influencing climate change, creates challenges as well as opportunities. As will be indicated in this report, the GHG impacts of waste management practices can be significant³ and highly variable. Consequently, decision makers need analytical frameworks and tools to compare the GHG emissions associated with various waste management practices and for various types of materials.

Until recently, the only clear linkages between waste management and GHGs were in the area of landfill gas control (i.e., collecting and combusting landfill gas). Through recent life-cycle work of members of government agencies in the United States and Canada, other GHG and waste linkages have been illuminated as well.

This report represents the culmination of a series of projects to develop and refine life-cycle GHG emission factors for specific materials commonly occurring in the Canadian residential and industrial, commercial, and institutional (IC&I) waste stream. The original report, “Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions” (ICF 2001) described the net GHG emissions for selected materials, across a partial life cycle, ending with various waste management fates. ICF was subsequently contracted by Environment Canada and Natural Resources Canada to expand the life cycles for materials included in the original report and to modify the methodology to reflect geographic differences in the fuel mix (and resulting GHG emissions) associated with electric power generation. The findings of these research efforts were included in two addenda to the original report (ICF 2004a, 2004b). This report – the “2005 Update” – presents the findings described in all three of the abovementioned documents as well as the results of research undertaken more recently.

The most recent research has included the addition of several materials that are common in the residential and IC&I waste streams and where the potential of alternative waste management options are of interest to Environment Canada and NRCan: electronics (personal computers, microwaves, TVs, and VCRs), white goods (e.g., washers, dryers, and refrigerators), copper wire, and tires. In addition, this report reflects efforts to improve the modelling of paper recycling by simulating open loop recycling – i.e., where the second generation products differ from the product being recycled – for each of the paper grades. Previously, all recycling material flows were assumed to be “closed loop” (e.g., newsprint is recycled and made into more newsprint). Open loops are also assumed for electronics and white goods. The emission factors

³ The waste sector is a significant source of GHG emissions on a national level; methane from landfills and carbon dioxide from waste combustion accounted for over 3 percent of Canada’s total GHG emissions in 2002 (Source: Environment Canada).

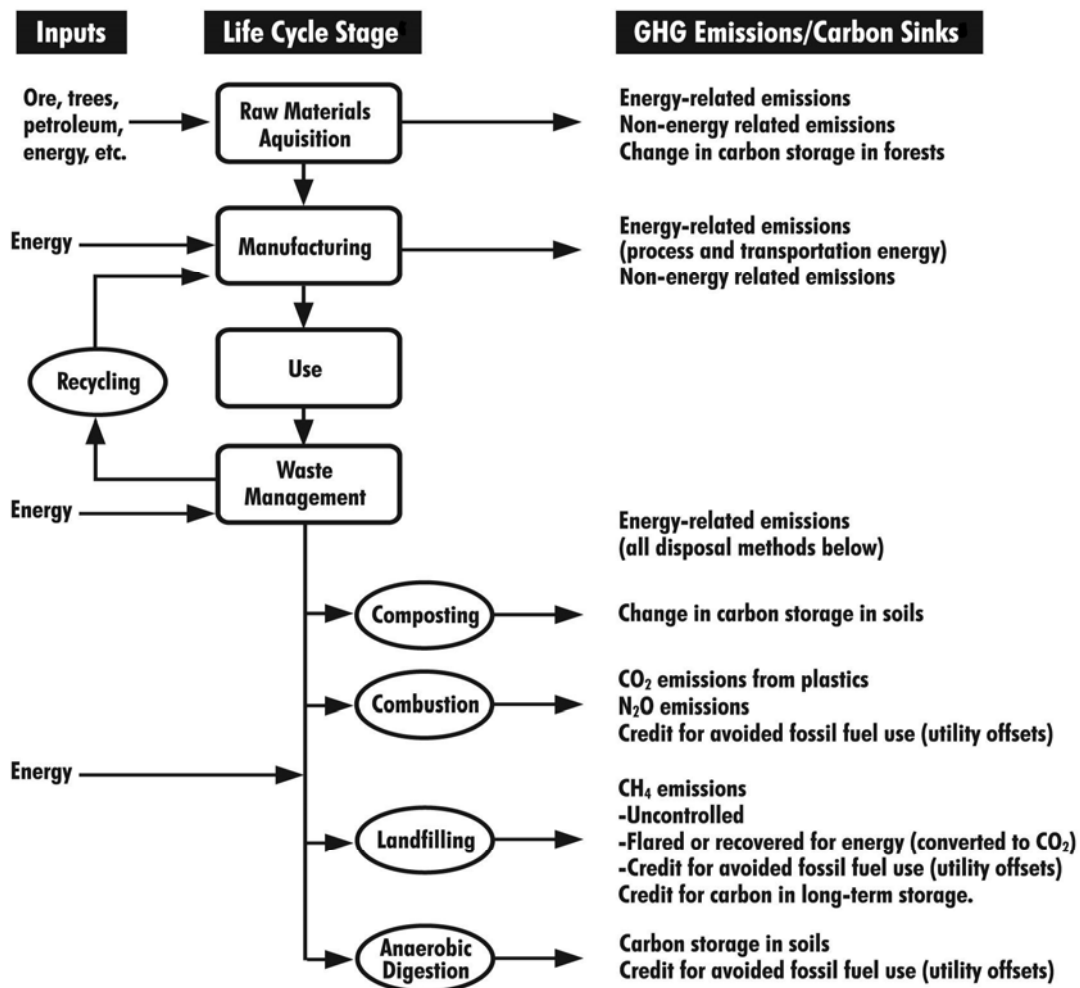
provided in this report also reflect updates to the data used to calculate emissions from electricity use.

The remainder of this report is designed to meet the following objectives:

1. Present the methodological framework used to estimate life-cycle GHG impacts of waste management in Canada; and
2. Describe the data and assumptions used to develop emission factors for each material and end-of-life management practice.

Figure 1 below provides an overview of the waste management life cycle evaluated in this report. The generalized flow diagram illustrates the various life-cycle stages for a material (e.g., manufacturing) and associated inputs and resulting GHG emissions or offsets.

Figure 1. Waste Material Life-cycle GHG Emissions and Offsets



Due to the complexity of this analysis, the report contains as much relevant information as possible and is structured in a straightforward and intuitive manner. The following is a brief description of the subsequent chapters of this report:

Methodology (Chapter 2) – This chapter explains the concept of a life-cycle GHG analysis and key steps in the process. Details on the concept of energy consumption for raw materials acquisition and manufacturing, for both virgin and recycled materials, are presented along with the energy and GHG characteristics of various waste management options including recycling, aerobic composting, anaerobic digestion, combustion and landfilling. Accounting issues related to landfill methane generation, carbon sinks, and transboundary material flows are also discussed.

Metals and Glass (Chapter 3) – This chapter provides an overview of the GHG impacts associated with waste management options for aluminum, steel, copper wire, and glass bottles. A basic explanation of the manufacturing processes (e.g., mining) is provided along with information and assumptions used to estimate GHG emission factors for each relevant waste management option.

Plastics and Tires (Chapter 4) – This chapter provides an overview of the GHG impacts associated with waste management options for high-density polyethylene (HDPE), polyethylene terephthalate (PET), other plastics, and tires. A basic explanation of the manufacturing processes (e.g., monomer and polymer production) is provided along with information and assumptions used to estimate GHG emission factors for each relevant waste management option.

Forest Products (Chapter 5) – This chapter provides an overview of the GHG impacts associated with waste management options for newsprint, fine paper, cardboard, and other paper. A basic explanation of the manufacturing processes (e.g., pulp production) is provided along with information and assumptions used to estimate GHG emission factors for each relevant waste management option.

Organics (Chapter 6) – This chapter provides an overview of the GHG impacts associated with waste management options for food waste and yard trimmings. A basic explanation of the information and assumptions used to estimate GHG emission factors is provided for each relevant waste management option.

Electronics and White Goods (Chapter 7) – This chapter provides an overview of the GHG impacts associated with waste management options for personal computers, televisions, microwaves, VCRs and white goods. A basic explanation of the information and assumptions used to estimate GHG emission factors is provided for each relevant waste management option.

Emission Factor Overview (Chapter 8) – This chapter provides a brief explanation of how the waste management emission factors may be used along with a summary of the emission factors themselves.

Appendix A – This appendix presents our approach for implementing the use of province-specific electricity GHG emission coefficients. Data on provincial electricity generation fuel mixes (e.g., coal by type, natural gas, hydro, nuclear) are combined with the appropriate carbon content factors to estimate how much eCO₂ is released to produce a gigajoule (GJ) of electricity in each Canadian province.

Appendix B – This appendix contains the detailed energy (electricity and fossil fuel) consumption tables that are a key component of our analysis. Information on current mix, retention rates, carbon coefficients, and process non-energy emissions is also presented here.

Our approach allows the reader to be selective in their use of this report or delve into the more in-depth aspects of energy and GHG life-cycle analysis. For example, the reader can simply

scan the aluminum section to extract the desired emission factors, or can review the methodology, entire aluminum section, and related appendices to obtain a more thorough understanding of the energy and GHG emission components of the aluminum life cycle.

In keeping with the priorities in the project, the documentation is relatively brief, addressing only the most important elements of the project.

2 Methodology

The key aspects of our methodology are described below:

- A streamlined life-cycle approach was used to characterize GHG emissions and sinks – that is, upstream and downstream effects were evaluated, and the scope was limited to only include GHG emissions and sinks;
- The life-cycle methodology included the following “Kyoto Gases” – carbon dioxide, methane, nitrous oxide, perfluorocarbons;
- GHG accounting techniques used in this report are largely consistent with Intergovernmental Panel on Climate Change (IPCC) GHG inventory accounting guidelines (<http://www.ipcc.ch/pub/guide.htm>), though the emission factors are not intended for use in the national inventory process;
- Given the ongoing international discussions over the specific categories of GHG sinks to include in GHG inventories and accounting at the national and project levels, the modelling framework was structured to report emission factors both with and without sinks;
- Because the economies of Canada and the US are so closely intertwined and the transboundary flows of primary and secondary materials and energy are so routine and seamless that the Canadian/US border is hard to distinguish from a life-cycle perspective, it is very hard to isolate exactly where the GHG emission effects occur with respect to political boundaries. The emission factors reported herein assume that Canadian waste management actions affect emissions and sinks within Canada.

The rest of this section presents the basic methodology used to develop emission factors to compare the GHG effects of various waste management practices. The discussion covers two broad topics:

1. Inputs and baselines for the streamlined life-cycle inventory; and
2. How these inputs are tallied and compared.

2.1 Inputs and Baselines for the Streamlined Life-Cycle Inventory

Evaluating the GHG emissions of waste management requires analysis of three factors:

1. GHG emissions throughout the life cycle of the material (including the chosen management option);
2. The extent to which carbon sinks are affected by manufacturing and disposing the material; and
3. The extent to which the management option recovers energy that can be used to displace energy that would be generated at an electric utility, thus reducing GHG emissions.

GHGs Emissions Relevant to Waste: The most important GHGs for purposes of analyzing residential and IC&I waste management options are carbon dioxide, methane, nitrous oxide, and perfluorocarbons. Of these, carbon dioxide (CO₂) is by far the most common GHG emitted in Canada (as it is in all other developed nations). Most CO₂ emissions result from energy use, particularly fossil fuel combustion. A great deal of energy may be consumed when a product is made and then discarded. This energy is used in the following stages: 1) extracting and processing raw materials; 2) manufacturing and fabricating products; 3) managing products at the end of their useful lives; and 4) transporting materials and products between each stage of their life cycles. The energy-related GHG emissions are estimated at all of these stages. Energy consumed in connection with consumer use of products is not evaluated. In addition, the energy consumed during use would be about the same whether the product was made from virgin or recycled inputs.

Methane (CH₄), a more potent GHG, is produced when organic waste decomposes in an oxygen-free (anaerobic) environment, such as a landfill. Landfills are a major source of CH₄ in Canada. CH₄ is also emitted when natural gas is released to the atmosphere during production of coal or oil, during production or use of natural gas, and from agricultural activities.

Nitrous oxide (N₂O) results from the use of commercial and organic fertilizers and fossil fuel combustion, as well as other sources. In addition to these emissions, for this project, N₂O emissions were estimated from only one management practice, waste combustion. Because N₂O emissions reflect a minor contribution to total emissions, the value from the U.S. analysis was used as the default value for Canada.

Perfluorocarbons (CF₄ and C₂F₆) are emitted during the reduction of alumina to aluminum in the primary smelting process. The source of fluorine, which produces CF₄ and C₂F₆ emissions, is the molten cryolite (Na₃AlF₆) in which the reduction of alumina occurs. Perfluorocarbons are formed during “anode effects,” which are periods when the fluorine in cryolite reacts with the carbon in the anode (a carbon mass of paste, coke briquettes, or prebaked carbon blocks), and in the carbon lining that serves as the cathode. Although the quantities of perfluorocarbons emitted are small, these gases are significant because of their high global warming potential. Recent improvements in Canadian smelting processes have reduced the occurrence of “anode effects” and the associated releases of perfluorocarbon emissions.

Carbon Sinks Relevant to Waste: Carbon, like many other elements, cycles through the earth’s air, water, land, and biota. A carbon sink is a process that removes carbon from the atmosphere. While the carbon is stored in pools – such as forests, soils, or landfills – it is not in the atmosphere contributing to the “greenhouse effect” (i.e., the trapping of heat close to the earth’s surface).

Key Definitions (from IPCC 2003)

Carbon stock: quantity of carbon in a pool

Carbon pool: the reservoir containing carbon

Carbon sink: a process that removes carbon from the atmosphere

Carbons sequestration: the process of increasing the carbon content of a pool other than the atmosphere

From a GHG accounting perspective, analysts handle the accumulation of carbon in sinks as being the mathematical opposite of emissions. That is, if emissions are given a positive sign, sinks are given a negative sign.

Avoided Electric Utility GHG Emissions Relevant to Waste: When a waste is used to generate electricity (either through waste combustion, anaerobic digestion, or recovery of CH₄ from landfills), it displaces fossil fuels that would otherwise be consumed by the electric utility. Energy-related fossil fuel combustion is the single largest source of GHGs in Canada.⁴ When waste is used to generate power that displaces fossil fuel-derived electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions.

Comparing GHGs

Carbon dioxide, methane, and nitrous oxide are very different gases when it comes to their heat-trapping potential. The IPCC has established carbon dioxide as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of one kilogram (kg) of carbon dioxide is 1. The GWPs used in this report come from the IPCC Second Assessment Report (IPCC 1996).

Methane has a GWP of 21. This means that one kg of methane has the same heat-trapping potential as 21 kg of CO₂.

N₂O has a GWP of 310. Perfluorocarbons are the most potent GHGs covered by this analysis; GWPs are 6,500 for CF₄ and 9,200 for C₂F₆.

For this project, emissions of carbon dioxide, methane, nitrous oxide, and perfluorocarbons are expressed as carbon dioxide equivalents (eCO₂). The eCO₂ value for one tonne of each of the other gases is determined by multiplying its GWP by one tonne.

2.2 How These Inputs are Talled and Compared

GHGs are emitted from: (1) the pre-consumer stages of raw materials acquisition and manufacturing and (2) the post-consumer stage of waste management. For this study, no GHG emissions are attributed to the consumer's use of any product because these emissions are not relevant from a waste management perspective.

In calculating emissions for the life-cycle scenarios, two different reference points can be used:

- In a "raw material extraction" approach (i.e., cradle-to-grave perspective), one can start at the point of raw material acquisition as the "zero point" for emissions, and add all emissions (and deduct sinks) from that point on through the life cycle.
- In a "waste generation" approach (solid waste manager's perspective), one can begin accounting for GHG emissions at the point of waste generation. All subsequent emissions and sinks from waste management practices are then accounted for. Changes in emissions and sinks from raw material acquisition and manufacturing processes are captured to the extent that certain waste management practices (i.e., recycling) impact these processes.

⁴ The energy sector accounted for 81 percent of all Canadian GHG emissions in 2002 (Source: Environment Canada).

Because it is the difference in emissions between the baseline and alternate scenarios that is meaningful, using either of these reference points yields the same results. A waste generation GHG accounting approach was used because it was considered to be more appropriate for waste managers and policymakers evaluating waste management options. Moreover, food discards and yard trimmings are important components of the waste stream; it is extraordinarily difficult to develop upstream emission estimates for these materials (and there are no clear options for recycling), so the “waste generation” perspective makes the most sense for evaluating GHG emissions for these materials. The waste generation approach defines the “standard” raw material acquisition and manufacturing step for each material as consisting of average GHG emissions based on the current mix of virgin and recycled inputs. Changes in the mix of production (i.e., higher proportions of either virgin or recycled inputs) result in incremental emissions (or reductions) with respect to this reference point. Consumer demand for a product is assumed to be insensitive to recycling rate, and thus increases in the recycling rate are assumed to displace a corresponding amount of production using virgin inputs.

Exhibit 2-1 indicates how the GHG sources and sinks were counted for each residential and IC&I waste management option to estimate net GHG emissions using the post-consumer reference point. For example, the top row of the exhibit shows that recycling (1) avoids GHG emissions from raw materials acquisition and manufacturing; (2) results in an increase in forest carbon sinks for wood-derived products; and (3) does not result in GHG emissions from waste management. The sum of emissions (and sinks) across all steps in the life cycle represents net emissions. The sections following Exhibit 2-1 explain each of the life-cycle stages included in our analysis.

Exhibit 2-1. Components of Net Emissions for Various Waste Management Options

Solid Waste Management Strategy	GHG Sources and Sinks		
	<i>Process GHGs from Raw Materials Acquisition and Manufacturing/Fabrication</i>	<i>Change in Forest or Soil Carbon Sink</i>	<i>Waste Management GHG Emissions and Sinks</i>
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture/fabrication from virgin inputs) and avoided process non-energy GHGs	Increase in forest carbon sink associated with forest products	Process emissions are counted in the manufacturing stage
Aerobic Composting	No emissions/sinks*	Possible increase in soil carbon after application of compost	Compost machinery emissions
Anaerobic Digestion	Baseline process emissions due to manufacture/fabrication from the current mix of virgin and recycled inputs	Possible increase in soil carbon after application of compost	Avoided utility emissions, no CH ₄ emissions (because capture efficiency is assumed to be 100%)
Combustion	Baseline process emissions due to manufacture/fabrication from the current mix of virgin and recycled inputs	No change	Nonbiogenic CO ₂ , N ₂ O emissions, avoided utility emissions
Landfilling	Baseline process emissions due to manufacture/fabrication from the current mix of virgin and recycled inputs	No change	CH ₄ emissions, long-term carbon sink, avoided utility emissions (in cases where CH ₄ is recovered for energy)

* No manufacturing GHG emissions are considered for composting of food scraps and yard trimmings because these materials are not considered to be manufactured.

2.2.1 GHG EMISSIONS AND CARBON SINKS ASSOCIATED WITH RAW MATERIALS ACQUISITION AND MANUFACTURING/FABRICATION

Virgin raw materials are used to make various materials including ore used to make metal products, trees used to make paper products, and petroleum or natural gas used to make plastic products.

Inputs to manufacturing/fabrication include: (1) energy, and (2) either virgin raw materials or recycled materials.

The GHG emissions associated with raw materials acquisition and manufacturing are: (1) process energy GHG emissions, (2) transportation energy GHG emissions, and (3) process non-energy GHG emissions (for aluminum). Each type of emission is described below. Changes in the carbon sink in forests are also associated with raw materials acquisition for paper products and this is discussed separately in Section 2.2.1.5.

2.2.1.1 Process Energy

Fuels: Process energy GHG emissions consist primarily of CO₂ emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO₂ emissions from combustion

of biomass are not counted as GHG emissions (see box on CO₂ Emissions from Biogenic Sources, below).

The majority of process energy CO₂ emissions are from combustion of fuels used directly, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel is also needed to extract the oil or mine the coal that is ultimately used to produce energy, and to transport these fuels to where they are used; thus CO₂ emissions from this “pre-combustion energy” are counted in this category as well. When electricity generated by combustion of fossil fuels is used in manufacturing, the CO₂ emissions from the fossil fuels are also counted.

CO₂ Emissions from Biogenic Sources

Canada and all other parties to the Framework Convention on Climate Change agreed to develop inventories of GHGs for purposes of (1) developing mitigation strategies and (2) monitoring the progress of those strategies. The Intergovernmental Panel on Climate Change (IPCC) developed a set of inventory methods to be used as the international standard. (IPCC, *Guidelines for National Greenhouse Gas Inventories* (three volumes), 1997.) The methodologies used in this project to evaluate emissions and sinks of GHGs will be consistent with IPCC’s guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO₂ emissions from biogenic sources. For many countries, the treatment of CO₂ releases from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would eventually cycle back to the atmosphere as CO₂ due to degradation processes. The focus of the Framework Convention on Climate Change is on anthropogenic emissions - emissions resulting from human activities and subject to human control - because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon’s biogeochemical cycle, and altering the atmosphere’s heat-trapping ability.

Thus, for processes with CO₂ emissions, if (a) the emissions are from biogenic materials and (b) the materials are grown on a sustainable basis, then those emissions are considered to simply close the loop in the natural carbon cycle -- that is, they return to the atmosphere CO₂ which was originally removed by photosynthesis. In this case, the CO₂ emissions *are not* counted. (For purposes of this analysis, biogenic materials are paper, yard trimmings, and food scraps.) On the other hand, CO₂ emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH₄ emissions from landfills *are* counted - even though the source of carbon is primarily biogenic, CH₄ would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH₄ formation.

Note that this approach does not distinguish between the timing of CO₂ emissions on a year-to-year basis, provided that the emissions occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO₂, it does not matter whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor).

In this analysis, the amount of energy and the mix of fuels that are required to make each of the materials under study are of interest (excluding food waste and yard waste as noted above), both from virgin inputs and from recycled inputs. The analysis covered four categories of paper products (newsprint, fine paper, cardboard and “other” paper), aluminum, steel, copper wire, glass bottles, high-density polyethylene (HDPE), polyethylene terephthalate (PET), “other” plastic, tires, white goods, personal computers, microwaves, and video cassette recorders (VCRs). The materials analyzed in this study were selected largely because they are common in the waste stream and relatively “energy intensive” to produce – and if the output of these processes (e.g. paper products, aluminum, copper wire, steel, etc.) can be reduced through recycling, then the “upstream” energy savings can be considerable.

Recycling most materials results in manufacturing energy savings (measured in gigajoules or GJ), but the effect is much more significant for materials that require energy-intensive primary processing. CO₂ combustion emissions range from about 50 kg per GJ for natural gas to nearly 87 kg per GJ for coal, but many manufactured products use less than 0.5 GJ/tonne to produce and so the GHG savings from recycling are relatively small. There are a few products, however, that require from 10 GJ per tonne or more to produce from virgin inputs (e.g., paper, steel, plastics, copper wire, and aluminum), and for these energy-intensive products the energy savings from recycling can yield CO₂ emission reductions of several tonnes of CO₂ per tonne of product recycled. Recycling these materials can lead to significant GHG reductions, due to the much lower amounts of energy required to manufacture from recycled inputs than from so-called “virgin” materials (e.g. recycled paper vs. pulpwood).

To estimate the GHG benefits of reducing or recycling the materials considered, the amount of energy required to make a tonne of the material and the breakdown of this energy by fuel type was estimated, including electricity. For electricity used in the life cycle, the GHG emissions are a function of the types and amounts of fuels used in electricity generation, which vary from province to province, as well as some losses of energy during transmission. Our approach for deriving electricity-related emission factors is described in Appendix A. For direct fossil fuel consumption (e.g., use of natural gas in on-site boilers), system efficiencies are intrinsically included in the energy consumption estimates. For each material, two sets of estimates were produced, one for manufacturing from virgin materials and one for manufacturing from recycled materials. The resulting energy use figures were multiplied by emission factors for each fuel to obtain the GHG emissions per tonne of material that result from fuel and electricity use at the manufacturing stage. The emission factors used for fuel combustion are summarized in Exhibit 2-2 and are taken directly from the Canadian GHG inventory (EC 2002).

Exhibit 2-2. Emission Factors for Fuel Combustion. Source: EC 2002

Fuel Type	Combustion kg CO₂/GJ	Combustion eCO₂ CH₄/GJ	Combustion eCO₂ N₂O/GJ	Precombustion eCO₂/GJ	Total kg eCO₂/GJ
Coal	86.80	0.00	0.01	6.42	93.23
Natural Gas	49.65	0.27	0.40	9.89	60.20
Kerosene & Stove Oil	68.54	0.13	4.03	17.73	90.42
Diesel	71.28	0.05	1.24	17.73	90.30
LPG	60.61	0.02	-	17.73	78.37
Distillate (Light Fuel Oil)	72.94	0.13	4.03	17.73	94.82
Residual (Heavy Fuel Oil)	72.71	0.63	4.03	17.73	95.10
Gasoline	68.09	0.47	2.80	17.73	89.09
Oil/ Lubricants	47.93	-	0.19	17.73	65.85
Petroleum (Non-specified)	73.11	0.05	0.33	17.73	91.23
Biomass	-	0.96	-	17.73	0.96
Tires	75.00	-	-	-	75.00

Electricity: The process energy GHG emissions also include the emissions produced by the use of electricity during raw material acquisition and manufacturing. In order to estimate the emissions from electricity, it was necessary to develop an end use emission factor that would allow power plant emissions to be pro-rated over kilowatt-hours of electricity end use. This was done for each province as well as for the entire nation, and the results are shown in Exhibit 2-3. In determining the electricity emission factor to be applied in computing the greenhouse emission impacts of reducing or recycling a particular material, the national factor was used for processes that are distributed throughout Canada, and a weighted mix of provincial factors was used for processes with a marked and important concentration in particular provinces. For example, the electricity associated with steel production from virgin inputs was assumed to be in Ontario, because that is where all the integrated blast furnace operations are located. For steel made from recycled scrap, the weighted average coefficient was developed from the electricity emission factors for each of the four provinces with electric arc furnaces, with the weighting determined by the share of mini-mill production capacity in each province. For aluminum, where primary production is situated in Quebec and BC – both of which have a high proportion of hydroelectric power in their electricity generation mix – and much of the overall fuel mix is based on electricity, GHG emissions are low despite the fact that energy intensity is high. This is the key reason the GHG emissions associated with Canadian aluminum production are so much lower than in the United States, where there is a greater reliance on coal-fired generation.

Note that in addition to the primary approach of simulating electricity-related emissions as a function of the provincial fuel mix, the analysis also offers alternate approaches of calculating emissions using the national average electricity emission coefficient (for purposes of evaluating

potential effects of scrap exports), or the U.S. average electricity emission coefficient. These options are described in detail in Appendix A.

Exhibit 2-3. Emission Factors for End Use Electricity

	Electricity Coefficients (kg eCO ₂ /kWh)			
	CO ₂	eCO ₂ N ₂ O	eCO ₂ CH ₄	eCO ₂ Total
Newfoundland	0.186777	0.000237	0.000029	0.187044
Prince Edward Island	1.040882	0.001092	0.000170	1.042143
Nova Scotia	0.666402	0.003536	0.000094	0.670031
New Brunswick	0.530629	0.001659	0.000077	0.532366
Quebec	0.011436	0.000018	0.000002	0.011456
Ontario	0.315821	0.001939	0.000040	0.317800
Manitoba	0.036350	0.000048	0.000002	0.036400
Saskatchewan	0.889836	0.000562	0.000011	0.890410
Alberta	1.032736	0.007900	0.000167	1.040802
British Columbia	0.025418	0.000096	0.000002	0.025516
Yukon	0.045239	0.001645	0.000072	0.046956
Northwest Territories	0.474858	0.011377	0.000488	0.486722
Nunavut	0.000000	0.000000	0.000000	0.000000
Canada	0.276270	0.001567	0.000036	0.277874

It is important to stress the approximate nature of this exercise. Our goal is to develop a set of robust emission factors that will support an estimate of the impact of waste reduction and recycling. The precise impact of recycling a particular item will vary with circumstances, and it would be virtually impossible to specify precisely and in detail the exact impact of a particular waste recycling action at a particular place and time. In the case of paper, for example, there are dozens of different products made with varying levels of recycled fibre in mills that use different fuels with varying efficiencies. Although it is impossible to say what the exact energy impacts of recycling a particular paper product will be, the impacts are large enough that it is worth developing approximate factors that will allow the value of waste reduction and recycling efforts to be assessed alongside other strategies for reducing GHG emissions. Details on energy consumption and other processes examined in this report are presented in Appendix B.

2.2.1.2 Transportation Energy

Transportation energy GHG emissions consist of CO₂ emissions from the combustion of fuels used to transport raw materials, intermediate products, manufactured goods, and wastes. It should be noted that despite being relatively small, collection and transport of waste is one of the major components of the waste management process over which the municipalities have control and therefore a potential area for municipalities to reduce emissions and other environmental impacts. A variety of sources were used to quantify the transportation-related emissions during raw materials acquisition (for virgin materials), manufacturing and fabrication, and

transportation to end-use. Specific sources and assumptions are explained in more detail in the material-specific discussions that follow.

2.2.1.3 Pre-Combustion Energy

Just as the life cycle includes raw material acquisition for the materials used in production (e.g., the wood used to make paper, or the bauxite used to make aluminum), there is also a “raw material acquisition” aspect to the fossil fuels used to supply energy throughout the life cycle. Examples of these pre-combustion emissions include CH₄ emitted from natural gas pipelines used to transport gas and CO₂ emitted from burning fuel in the engines that drive oil wells.

Separate factors were developed for petroleum, natural gas, and coal. In all three cases, the pre-combustion emissions are a significant proportion of the emissions at the point of combustion, and thus have a significant effect on the overall emissions picture.

Petroleum and Natural Gas: The pre-combustion emission factors for petroleum and natural gas were derived from information in the national GHG inventory on emissions (EC 2002). Our basic process was to divide emissions by output to develop a pre-combustion emission factor for both petroleum and natural gas. The main issues involved in developing these factors were determining which emissions should be included, and how to allocate them to either petroleum or gas (as a practical matter, gas and oil are extracted and processed in many of the same steps).

Detailed calculations on pre-combustion are based on data shown in Appendix B (this appendix provides supporting data for many of the specific and detailed supporting data sets used throughout the remainder of this report). Exhibit B-1 and Exhibit B-2 display 2001 GHG emissions associated with the production, refining, and transportation of natural gas and petroleum in Canada. These numbers are taken directly from the national GHG inventory and include the energy-related emissions of the oil and gas industry, the energy-related emissions of the petroleum refining industry, the energy-related emissions of pipeline energy use,⁵ and the fugitive emissions from oil and gas production.

Exhibit B-3 provides the quantities of Canadian oil and gas outputs for 2001. Total natural gas production was about 6,500,000 TeraJoules (TJ), and total refined petroleum product (RPP) production was about 3,700,000 TJ, thus the ratio of gas to RPP output was 64%:36%. These ratios were used to apportion emissions from the sectors that pertain to both natural gas and RPP, viz. fossil fuel production, pipelines, venting, and flaring.

The final step in the calculation was to divide the appropriate share of the fossil fuel GHG emissions by the natural gas and RPP output values (from Exhibits B-1 and B-2, respectively), in order to get the pre-combustion factor. These factors are 9.9 kg eCO₂ per GJ of natural gas, and

⁵ It is not clear whether electricity consumption associated with pipelines is included in these values.

17.8 kg eCO₂ per GJ of RPP. The RPP value is assumed to apply to diesel, heavy fuel oil, light fuel oil, and LPG (liquefied petroleum gas).

Coal: The pre-combustion emission factor for coal is 6.42 kg eCO₂ per GJ of coal, and was obtained from U.S. EPA's Fuel Life Cycle Emissions Model (FULCEM), developed based on life-cycle data provided by Franklin Associates. The model, which provides emissions associated with individual life-cycle elements for fuels, is currently in draft form, is based on U.S. data, and is not publicly available. A source of Canadian data on energy used in coal mining and processing could not be found.

2.2.1.4 Process Non-energy

Some GHG emissions occur directly in the manufacture of certain materials and are not associated with energy consumption. These emissions are referred to as process non-energy emissions. For example, the production of steel, cement or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or CaCO₃); the manufacture of lime/clinker results in CO₂ emissions. Other process non-energy GHG emissions are associated with production of plastics, office paper, and tissue paper. In some cases, process non-energy GHG emissions are only associated with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used. These emissions are generally insignificant, with the exception of PFC and CO₂ emissions from anodes consumed in primary production of aluminum. Values were developed for non-energy emissions for aluminum and the various electronics (i.e., personal computers, microwaves, and VCRs) because they contain aluminum.

2.2.1.5 Carbon Sinks (forest carbon)

The only reduction in net GHG emissions in the stages of raw materials acquisition and manufacturing is the additional carbon storage in trees associated with recycling of paper products.

One of the processes that influence the cycling of carbon is the uptake or release of carbon from forests. When trees are cleared for agriculture or other activities, carbon is released (generally in the form of CO₂). On the other hand, when forests are planted and allowed to grow, they absorb atmospheric CO₂ and store it in the form of cellulose and other materials. When the rate of uptake exceeds the rate of release, carbon is said to be stored in the forest carbon pool.

When paper products are recycled, trees that would otherwise be harvested are left standing. In the short term, this results in a larger amount of carbon remaining in the forest pool, because the standing trees continue to store carbon, whereas paper production and use tends to release

carbon.⁶ In the long term, some of the short-term benefits disappear as market forces result in less planting of new managed forests than there would otherwise be, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus accumulating carbon rapidly).

A mass balance approach was used to estimate the benefits of recycling. This approach estimates the short-term effect – retaining carbon in forests – of reducing harvest rates, rather than continuing to remove trees and transform carbon into relatively short-lived products like paper. The mass balance, shown in Exhibit 2-4, is driven by the relationship between:

- Carbon inputs to paper mills as a proportion of carbon in trees harvested from forests (assumed to be a ratio of 60 percent, see column (a) in Exhibit 2-4);
- Carbon content of mill outputs as a proportion of carbon content of mill inputs (assumed to be a ratio of 90 percent for thermomechanical pulping used to manufacture newsprint, and a ratio of 60 percent for chemical pulping used in the manufacture of fine paper, corrugated, and other paper, column (b) in Exhibit 2-4); and
- The carbon content of paper (assumed to be 45 percent for all paper types, column (d) in Exhibit 2-4).

Our treatment of recycling assumes that overall demand for products is relatively constant, and thus each incremental tonne of recycled material displaces an equivalent mass of virgin inputs. Within this framework, one must account for the loss rates in the recycling process. As noted above, the losses are subdivided into those between the point of generation (i.e., at curbside,

⁶ The basic relation is that the forest carbon inventory in any year equals the carbon inventory the year before, plus net growth, less harvests, less decay. Thus, when harvests are reduced the inventory increases. However, when inventories become high relative to the carrying capacity of the land, the rate of growth decreases because net growth [the rate at which growth exceeds decay] declines.

where waste tonnage is often measured) and leaving the gate of a materials recovery facility (MRF, i.e., a facility where recycled materials are sorted, column (g)), and the losses between input and final output of the remanufacturing processes, column (h)). The total losses range from about 39 percent for fine paper to 21 percent for newsprint; thus recycling process retention ranges from 61 percent to 79 percent (see column (i)). The forest carbon benefit of recycling is then calculated as the product of carbon retention rate for production of paper from 100 percent virgin inputs (column f) multiplied by (b) the recycling process retention rate (column i).

The calculation includes a conversion from the mass of carbon to the mass of carbon dioxide equivalent, as the GHGs in this report (and most GHG documents) are normalised to units of CO₂. This conversion takes place in column (f).

Exhibit 2-4. Mass Balance Approach for Forest Carbon Sink

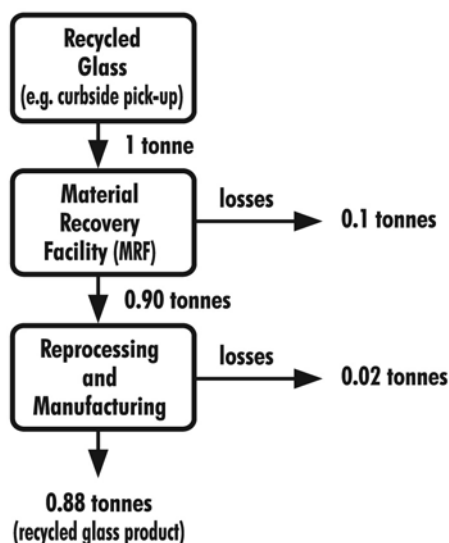
Paper Type	Virgin Paper System Efficiency			(d) C content of paper (wet wt)	(e) Tonnes C not harvested per wet ton paper not made from 100% virgin inputs (= d / c)	(f) Tonnes eCO ₂ /tonne of 100% virgin paper not produced (= e * 44 gm CO ₂ /12 gm C)	Recycled Paper System Efficiency			Benefit of recycling, based on displacing 100% virgin paper (j) Tonnes eCO ₂ / tonne paper recycled (= f * i)
	(a) Mill Input/Forest Cut Ratio	(b) Mill Carbon Output/Input Ratio	(c) Carbon retention (mill output: forest out) (= a * b)				(g) Tonnes exiting MRF/tonnes collected	(h) Mill Carbon Output/Input Ratio	(i) Carbon retention (mill output/ paper collected) (=g * h)	
Newsprint	60%	90%	54%	45%	0.83	3.06	0.98	0.81	79%	2.42
Fine Paper	60%	60%	36%	45%	1.25	4.58	0.95	0.64	61%	2.77
Cardboard	60%	60%	36%	45%	1.25	4.58	0.98	0.69	68%	3.11
Other Paper	60%	60%	36%	45%	1.25	4.58	0.95	0.64	61%	2.77

2.2.2 GHG EMISSIONS AND CARBON SINKS ASSOCIATED WITH WASTE MANAGEMENT

As shown in Exhibit 2-1 there are, depending on the material, up to five post-consumer waste management options: recycling, composting, anaerobic digestion, combustion, and landfilling. This section describes the GHG emissions and carbon sinks associated with these waste management options.

Recycling: When a material is recycled, it is used in place of virgin inputs in the manufacturing process. Thus, the avoided GHG emissions from remanufacture using recycled inputs is calculated as the difference between (1) the GHG emissions from manufacturing a material from 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material from 100 percent virgin inputs (including the process of collecting and transporting the recyclables) after accounting for loss rates. Figure 2 provides an example of loss rates that are applied for glass bottles. There are no GHG emissions at the waste management stage because the recycled material is diverted from waste management facilities.⁷

Figure 2. Glass Recycling Loss Rates



Many of the materials considered in the analysis were modelled as being recycled in a “closed loop” where the second generation product is the same as the first (e.g., glass bottles are recycled into new glass bottles). In cases where there is significant “open loop” recycling (i.e., where

⁷ If the product made from the recycled material is later composted, combusted, or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material.

some of the second generation products are different than the original products), energy and GHG estimates for the second generation product were developed based on both virgin inputs and recycled inputs. Open loops for paper products (newsprint, fine paper, cardboard, other paper), copper wire, electronics, and white goods were simulated.

Composting: When organic materials are composted aerobically, most of their organic mass quickly decomposes to CO₂. The materials that may be composted (e.g., yard trimmings, food discards) are all originally produced by trees or indirectly by other plant material. As described earlier, the CO₂ emitted from these materials during composting is considered to be biogenic CO₂, and thus is not counted in the GHG emissions.

It is likely that well-managed compost operations do not emit CH₄ because they typically maintain an aerobic environment with proper moisture content to encourage aerobic decomposition of the materials. Although aerobic composting may result in some CH₄ production (due to anaerobic decomposition in the center of the compost pile), the CH₄ is most likely oxidized to CO₂ when it reaches the oxygen-rich surface of the compost pile (US EPA 2002). It was thus assumed that aerobic composting results in negligible CH₄ releases. Some potential exists for the compost process to result in production of humic material (natural organic polymers, which degrade at a slow rate), which can then persist in soils to which compost is applied. This can enhance long-term carbon storage in the soils.

Anaerobic Digestion: CH₄ is intentionally produced during anaerobic digestion and is subsequently collected and burned for its energy value. The key issues for estimating GHG emissions from this type of waste management are the CH₄ conversion rate and the efficiency of the gas collection system.

After initial digestion, the waste mass is subsequently stabilized through an aerobic composting process. As in composting of yard trimmings or food discards, the finished compost is generally applied to soils. Some potential exists for the application of compost to result in long-term carbon storage in the soils but data in this regard are unavailable.

Collection and Transportation: Another component of this waste management strategy is collection and transportation. The trucks used to collect materials for recycling, composting or anaerobic digestion and then move it from transfer stations typically consume diesel fuel, which emits 2.7 kg eCO₂ per litre of fuel. GHG emissions from any particular fleet of collection and waste transfer trucks can be computed by multiplying total consumption of diesel fuel by this factor. Dividing that result by the total amount of waste moved in tonnes will yield emissions per tonne of waste. The results vary over a wide range (1-20 kg eCO₂ per tonne of waste) depending on the distances traveled by the collection trucks and the efficiency of the trucks and their operation, but a typical mid-range value is 10 kilograms eCO₂ per tonne of waste managed (or 0.010 tonnes eCO₂ per tonne of waste). Multiplying this value by the carbon coefficient for diesel fuel results in an estimated energy consumption value of 0.11 GJ/tonne. It requires exceptionally long distances, low capacity factors, or inefficient vehicles for emissions to be as high as 20 kg eCO₂ per tonne of waste. This relatively low value can be reduced further by increasing the capacity of the trucks, the efficiency of their routing and operation, or the fuel efficiency of the engines. Transportation-related emissions will often increase significantly as

recycling and central composting operations are implemented, due to the need for additional, specialized vehicles and/or separate collections for the different waste streams. However, although the local environment is impacted, in the larger energy picture, this portion is a relatively small component.

Combustion: When waste is combusted, two types of GHGs are emitted: CO₂ and N₂O. The non-biogenic CO₂ emitted during the combustion (i.e., CO₂ from plastics), collection, and transportation of waste is counted along with the combustion N₂O toward the GHG emissions from combustion. The emission factors associated with collection and transportation of waste for combustion are assumed to be equivalent to the factors discussed above for anaerobic digestion (0.010 tonnes eCO₂ per tonne of waste). The biogenic CO₂ emitted during the combustion process is not included in the GHG emissions.

Since most waste combustors produce electricity that substitutes for utility-generated electricity, the net GHG emissions are calculated by subtracting the utility GHG emissions avoided from the gross GHG emissions. Utility GHG emission offsets are a function of the fuel types used to generate electricity and the efficiency of the power generation system. The emission factors presented in this report assume that displaced electricity would otherwise have been generated by burning natural gas in a combined cycle power plant.⁸

Landfilling: When organic matter such as leaves or paper is landfilled, some of the material decomposes anaerobically and releases CH₄. Some of the remaining organic matter never decomposes at all, but instead becomes stored carbon. The landfilling of metals and plastics does not result in either CH₄ emissions or carbon storage. Plastics are derived from fossil fuels, but because the fossil carbon is not originally counted as an emission when it is extracted, counting its disposal in landfills as a sink would be inappropriate from a carbon accounting perspective.

At some landfills, virtually all of the CH₄ produced is released to the atmosphere and counts towards the gross GHG emissions for these landfills. At other landfills, CH₄ is captured for flaring or combustion with energy recovery (i.e., electricity production, direct use). Most of the captured CH₄ is converted to CO₂, which is not counted as a GHG because it is considered biogenic. With combustion of CH₄ for energy recovery, an emission offset estimate is made for the electric utility GHG emissions avoided. Regardless of the fate of CH₄, an emission offset estimate is made for the landfill carbon storage associated with landfilling of some organic materials. Separate emission factors for landfills with and without landfill gas (LFG) recovery systems, and for the “average” Canadian landfill (based on an estimate of the proportion of landfills with and without LFG recovery) were developed.

As with waste designated for anaerobic digestion or combustion, the collection and transportation of waste for landfilling is also associated with a default emission factor (0.010

⁸ The spreadsheet model that supports this analysis has the capability of varying this assumption.

tonnes eCO₂ per tonne of waste). Fuel and electricity use for the buildings and equipment at landfill facilities also result in GHG emissions, but these are even smaller, typically about ten times smaller, than emissions from waste transportation. The level of emissions depends on specific operational characteristics of the facility, emissions intensity of the grid electricity being used, etc., but a typical benchmark for emissions from these facilities is 0.5-1.0 kg eCO₂ per tonne (0.0005-0.001 tonnes eCO₂ per tonne) of waste managed (Torrie Smith Associates, 2004).

In addition to the emissions from buildings and general equipment, landfills are uniquely associated with emissions from the use of heavy equipment. The large bulldozers used at landfills emit GHG emissions on a scale that is usually smaller than, but on the same order of magnitude as, the emissions from the waste collection truck fleet. As usual, emissions for individual landfills will vary, but diesel consumption in the range of 1.5 litres per tonne of landfilled waste is a representative benchmark. This equates to GHG emissions of about 4 kg eCO₂ per tonne, or 0.04 GJ/tonne of waste landfilled.

2.3 Accounting Issues

To conclude the discussion of methodology, several accounting issues that arise in estimating the life-cycle GHG emissions associated with waste management are briefly addressed.

2.3.1 LANDFILL GAS – METHANE COMMITMENT VS. WASTE-IN-PLACE METHODS

National GHG inventories report emissions of CH₄ gas from landfills on an annual basis. The emissions are generated primarily from waste that was placed in the landfill in earlier years; there is virtually no contribution from the waste sent to landfill during the inventory year because there is a lag time between waste placement and methane generation.

In the method for this project, the GHG impact of waste diversion was estimated based on the CH₄ that will *eventually* be emitted (or avoided) as the result of waste sent to (or diverted from) landfills. As such, the CH₄ emissions being counted are in the future relative to the year in which the waste management action occurs. This approach to counting CH₄, sometimes called the *methane commitment* method, is perfectly reasonable for an analysis that is intended to support the strategic planning of an organization that has control over the amount of waste sent to landfill in the inventory year. The CH₄ commitment method counts CH₄ differently from the conventional waste-in-place approach, but in both cases there is no double counting between analyses conducted with the two different methods for any common historical year.

2.3.2 CARBON SINKS

Estimating carbon storage in our methodology is somewhat different from landfill CH₄. In this case, the carbon that is being stored in the landfill is carbon that, according to IPCC inventory conventions, would have been released to the atmosphere within the same year. The carbon sink

assumptions embedded in the coefficients here are analogous to the allowance for carbon sinks that is permitted with respect to furniture and other long-lived forest products.⁹

The emission factors were developed both with and without carbon sinks. Including landfill carbon in the emission factor has the effect of reducing the net benefit of diverting material from landfills. Including sinks has the effect, however, of significantly reducing the net GHG emissions from landfills. In fact, for some materials a landfill with gas recovery may appear as a net sink for GHG emissions if the storage of carbon is included in the calculation.

2.3.3 TRANSBOUNDARY FLOW OF MATERIALS

The emission factors developed in this report are based on the assumption that material recycled in Canada displaces or impacts Canadian production facilities. This assumption is not consistent with the approach used in GHG inventories, which attempt to rigorously demarcate national emissions and sinks in accord with national boundaries. However, the life-cycle perspective that is used here is intrinsically broad in its perspective in that it tracks upstream and downstream effects. Given that the Canadian economy is highly integrated with those of the rest of North America (and especially with respect to aluminum and paper, economies of Brazil, Australia, China, and elsewhere), it is difficult (and in some ways counterproductive) to truncate the life cycle at the national border. This section explores a few of the transboundary issues that are particularly important.

Aluminum: A significant portion of aluminum cans recycled in Canada is actually remelted in the United States. One could argue that Canadian can recycling therefore displaces primary aluminum smelting in the United States which has much higher levels of GHG emissions per tonne of aluminum than Canadian smelters, which are more modern and which use hydroelectricity almost exclusively. The use of Canadian emission factors for estimating the GHG impact of aluminum recycling therefore probably underestimates the actual greenhouse impact of recycling Canadian aluminum cans. By the same token, it may also be the case that aluminum can recycling has very little impact on GHG emissions *within* Canada. A sensitivity analysis was conducted on the import/export issue by selecting different values for the electricity emissions associated with virgin and recycled production, e.g., one can use a Canadian value for virgin production and a US value for recycled production.

⁹ For example, the IPCC guidelines note that carbon stored in long-lived wood products can be counted as a sink as part of the forest carbon flux method (IPCC 1997).

Paper Products: Canada imports a significant amount of used paper, in the case of newsprint about as much as is generated from Canada's own recycling efforts. It is possible therefore that increased paper recycling in Canada would have the effect of offsetting these imports, but it is very difficult to determine what the net effect would be on GHG emissions. Within Canada, however, it raises the possibility that increased paper recovery by Canadians would not translate into increased use of recycled material by Canadian pulp mills. As with aluminum, the import/export issue can be addressed through sensitivity analysis.

3 Metals & Glass

This section provides details on the development of emission factors for aluminum, steel, copper wire, and glass bottles. These materials are grouped together in this section because they all share relatively similar and energy intensive upstream processes, including mining, processing, and smelting or melting. These materials are also inert; therefore, none of these materials contributes to downstream emissions associated with the decomposition of organic material.

The following sections provide details on the energy associated with recycling, and combustion of aluminum, steel, copper, and glass bottles.¹⁰

3.1 Aluminum

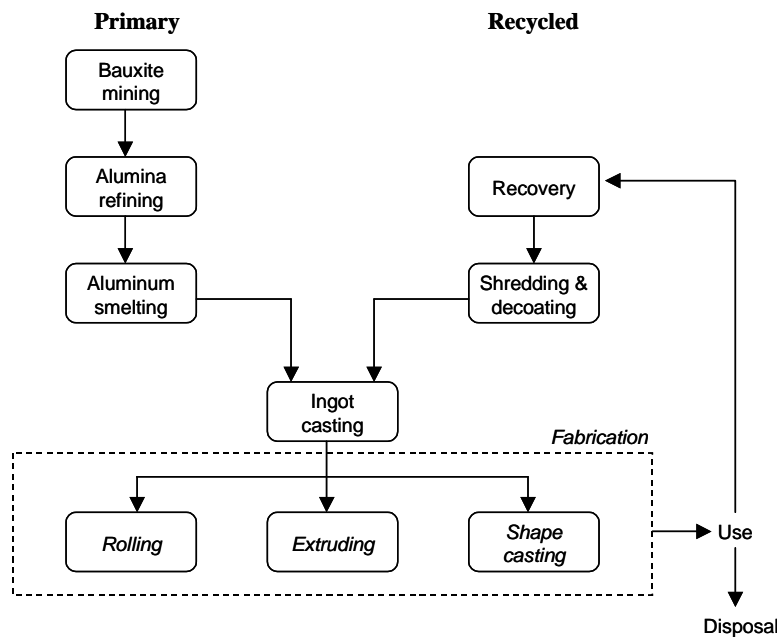
The manufacture of aluminum is one of the most energy-intensive industrial processes occurring within Canada's borders, and the GHG emissions associated with electricity and fossil fuel consumption in this process, as well as non-energy emissions, can be substantial. The life cycle of aluminum production includes bauxite ore mining, alumina production, carbon anode production, aluminum smelting, ingot casting, and fabrication. Recycling aluminum materials results in significant reductions in energy consumption and GHG emissions by avoiding the upstream manufacturing emissions associated with primary aluminum. This section provides information on how the aluminum life cycle was expanded, along with background information and data sources.

The primary source of the aluminum life-cycle information presented in this chapter is a report published by the International Aluminum Institute (IAI) (formerly the International Primary Aluminum Institute) in 2000, entitled *Aluminum Applications and Society: Life Cycle Inventory of the Worldwide Aluminum Industry With Regard to Energy Consumption and Emissions of Greenhouse Gases, Paper 1 – Automotive*.¹¹ This report presents comprehensive information on electricity and fossil fuel consumption for each stage of the aluminum life cycle, including production of ancillary (or feedstock) materials and transport of materials. Figure 3 shows the production flows for primary and recycled aluminum.

¹⁰ Landfilling, anaerobic digestion, or composting were not covered in the rest of the chapter. The only energy associated with landfilling of these materials is 0.15 GJ/tonne for waste collection vehicles, transport to the landfill, and heavy equipment operation at the landfill. These materials are also non-reactive in an anaerobic digester, and the energy associated with this disposal option for these materials is 0.11 GJ/tonne for collection vehicles and transport to the digestion facility. Metal and glass materials are typically not composted due to their inertness and interference with the compost turning/aeration process.

¹¹ Although this paper focuses on automotive aluminum products, the energy and emission characteristics are assumed to be identical regardless of the end use of the product. As discussed below, the raw material acquisition and manufacturing steps dominate the energy and emission profile, and the product preparation steps (i.e., fabrication) have a very minor effect. Note that IAI published a subsequent (2003) paper with a more complete life cycle analysis with additional environmental emissions, but the 2000 paper remains the source of energy data.

Figure 3. **Primary and Recycled Aluminum Production Flows**



The expanded methodology for aluminum as described in this report expands the scope to include several important elements that were not addressed in the original (2001) analysis. The original methodology was based on electricity and energy consumption for primary aluminum smelting, and an assumed 95% reduction in energy for recycled aluminum compared to virgin aluminum. It included one of two important “non-energy” GHG emission sources: primary aluminum production can result in reaction of fluorine with carbon in the anodes to inadvertently generate perfluorocarbon (PFC) emissions during the smelting process.¹² In addition to these components of the life cycle, the expanded methodology includes detailed information on electricity consumption and fossil fuel use for each step in the cycle, from mining of bauxite ore to shredding and decoating of recycled aluminum. It also includes CO₂ emissions associated with the consumption of carbon anodes in the primary (virgin) aluminum production process.

The aluminum material category covers three distinct product types: rolled sheet (e.g., cans and airplane skin), extruded (e.g., window frames and structural members), and shape cast (e.g., automotive engine components) aluminum material types. These three basic forms of aluminum in the marketplace differ only in the fabrication step of the life cycle, which contributes only a small fraction of total energy and emissions.

¹² This is referred to as an “anode effect,” i.e., a condition where the optimal concentration of alumina in the crucible is not maintained, and an electrochemical process involving the cryolite bath results in the production of PFCs.

Electricity and fossil fuel consumption estimates for the manufacture and fabrication of aluminum throughout its life cycle were drawn from the IAI report (IAI 2000). Although these values represent worldwide averages, rather than Canadian estimates, they are considered among the best information readily available. Electricity-related emissions and non-energy emissions (PFCs from anode events and CO₂ from anodes) are based on Canadian data (EC 2002). Aluminum is estimated to contain 48 percent virgin content on average¹³, and the post-consumer recycling retention rate is 84 percent (Enviros-RIS 2000). Exhibit B-6 through Exhibit B-11 in Appendix B show the detailed electricity and energy data associated with raw materials acquisition, manufacturing and fabrication, and transportation, and the ensuing discussion builds on these data sets.

The net GHG emission factors for the various waste management options for aluminum are shown in Exhibit 3-1, and their derivation is discussed below.

Exhibit 3-1. GHG Emissions from Waste Management Options for Aluminum (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE) - National Average
Aluminum	(6.49)	0.01	0.01	0.01

¹³ The recycled content of aluminum does not affect the physical properties and economic value of this material.

3.1.1 RECYCLING

Recycling aluminum provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials. The GHG emission benefits occur through a reduction in the process and transportation energy emissions, and process non-energy (perfluorocarbons) emissions associated with virgin production. The GHG emission impacts of recycling aluminum are presented in Exhibit 3-2. The derivation of these emission impacts are described in the remainder of this section.

Exhibit 3-2. Recycling Emissions for Aluminum (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Waste Management Option	Process Energy Emissions	Transportation Energy Emissions	Process Non-Energy Emissions	Net Emission Factor (=a + b + c)
Recycling	(2.98)	(0.20)	(3.31)	(6.49)

3.1.1.1 Raw Materials Acquisition

Virgin Product: The raw materials acquisition step for the production of virgin aluminum requires bauxite mining, alumina refining, and carbon anode production.

- **Bauxite Mining**: Mining of bauxite ore is the first step in the aluminum production process. The ore is acquired through standard mining practices (usually strip-mining), and then transported to facilities for processing where it is crushed and cleaned prior to transport via ship, rail, or truck to alumina refining facilities. Bauxite ore is a global commodity produced in Brazil, Australia, and elsewhere. Canada imports virtually all of the bauxite ore used in its alumina production facilities. At this stage, the primary source of emissions is from diesel mining equipment and ore processing equipment. It takes approximately 5.1 tonnes of bauxite ore to produce 1.9 tonnes of alumina, which in turn produce 1 tonne of aluminum (IAI 2000).
- **Alumina Refining**: At this stage the bauxite ore is processed through the Bayer refining process. The ore is heated and subjected to a caustic digestion process to produce soluble sodium aluminate or “green liquor,” which is then clarified and treated with gibbsite to induce the precipitation of aluminum trihydrate. The aluminum trihydrate is then calcinated in a fluidized bed or rotary kiln at 980 - 1,300 degrees Celsius to produce alumina. Canada produces about 15 percent of the alumina required for its aluminum smelting industry (Wagner 2004) with the remainder imported from Australia, the United States, and other countries. Electricity is directly consumed in this step, as well as fossil fuels for heating and production of ancillary materials such as caustic soda and lime.
- **Carbon Anode Production**: Carbon anodes are a key component of the electrical reduction of alumina to produce aluminum. Depending on the type of aluminum smelter being used, newer “prebaked” cells, and older Soderberg or “in-situ baked” cells are used for the electrochemical process. Carbon anodes are typically produced using a mixture of calcinated coke and pitch that is then baked to produce a monolithic mass that is fed into

the cell. Based on the national GHG inventory's estimates of CO₂ emissions from anodes, and national primary aluminum production, approximately 0.63 tonnes of carbon anode are consumed per tonne of aluminum produced, though the IAI (2000) estimates the worldwide average to be 0.45 tonnes C/ tonne aluminum.

Recycled Product: The raw material acquisition step for the production of recycled aluminum involves a collection and sorting process. According to IAI (2000), this step includes sorting and processing the material to ensure impurities are removed that would hinder the remelting process. Recovered aluminum scrap is typically shredded and heat treated to remove any coatings or paint material. Electricity and fossil fuels are used in this step to operate machinery and heat aluminum and this energy is included in the life cycle.

3.1.1.2 Manufacturing and Fabrication

Virgin Product: The manufacturing and fabrication step for the production of virgin aluminum consists of aluminum smelting, ingot casting, and fabrication.

- Aluminum Smelting: The aluminum smelting process consists of adding alumina to a molten cryolite bath and applying a high level of electrical current through the carbon anode and cathode circuit to induce the reduction of alumina to produce aluminum. This process, known as the Hall-Heroult process, consumes vast amounts of electricity, and therefore results in indirect emissions from electricity generation as well as direct CO₂ emissions from carbon anode consumption. As noted above, the aluminum smelting process is associated with a phenomenon known as "anode effects" that results in the production of PFCs, which are highly potent GHGs. In order to estimate the emissions from PFCs and carbon anode consumption specific to Canadian aluminum smelting, the aluminum smelting CO₂ and PFC emissions reported in the *2001 Greenhouse Gas Emissions Inventory Summary for Canada* (EC 2002) were used, which were 4,160 and 6,000 kt eCO₂ respectively, and divided that by the total 2001 estimate for primary aluminum production. The result is an estimated PFC emission factor of 2.32 tonnes of eCO₂ per tonne of aluminum produced, and an estimated direct CO₂ emission factor of 1.61 tonnes eCO₂ per tonne of aluminum produced. Exhibit B-12 identifies the information sources and provides the data used to estimate PFC and direct CO₂ emissions.
- Ingot Casting: In this step the molten aluminum is drawn from the smelting cell and processed to remove any impurities and adjusted for desired alloy. The molten aluminum is then transferred to various types of molds to produce ingots, semifabricated, and final products. Electricity and fossil fuels are used in this step to operate machinery and heating of holding furnaces.
- Rolling, Extruding, and Shape Casting: Once the sheet or billet ingots are produced, they are often transported to fabrication facilities where the ingots are shaped and formed, generally using large industrial machinery, into the desired product. The primary fabrication steps are rolling, extruding, and shape casting. The rolling process consists of compressing aluminum using rollers under high pressure to produce sheet with a desired thickness. Extrusion consists of forcing aluminum through a prefabricated die to produce

aluminum with a given form or shape. The shape casting process involves heating aluminum to a molten state and then injecting or pouring it into a prefabricated die or mold to produce a given shape. Each of these fabrication processes uses electricity and fossil fuels to operate machinery and heating of aluminum.

Recycled Product: The manufacturing and fabrication step for the production of recycled aluminum consists of secondary aluminum smelting and fabrication.

- **Secondary (Recycled) Smelting:** The recovered aluminum scrap is then processed and sorted, and then remelted to produce secondary sheet or billet aluminum ingots. Electricity and fossil fuels are used in this step to operate machinery and to heat aluminum.
- **Rolling, Extruding, and Shape Casting:** This fabrication step is the same as for virgin aluminum materials above, and has the same energy requirements.

3.1.1.3 Transportation

For both virgin and recycled production, each of the steps from raw material acquisition to fabrication has transport-related emissions associated with them, typically through the use of fuel oil or diesel petroleum products. The energy values used for transportation are based on IAI (2000), and thus reflect global averages rather than estimates derived specifically for Canada.

3.1.2 LIMITATIONS

The complexity of the aluminum manufacturing and disposal/recycling system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent average international conditions that may not accurately characterize national or site-specific conditions. For example, the raw material acquisition and manufacturing energy data represent an average global aluminum manufacturing (IAI 2000). There is likely to be some variation between individual aluminum production facilities with respect to energy consumption efficiency and fuel type. A key component of aluminum production emissions – perfluorocarbons – is estimated using Canadian GHG Inventory data (EC 2002), which provides a national component to the methodology. Site-specific variability is also a concern with each of the end-of-life management options (e.g., transport distances). In addition, these values do not address international cross-border flows. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with aluminum recycling, landfilling, and combustion activities from a national average perspective.

3.2 Steel

The life cycle for virgin steel starts with the raw materials acquisition process, which consists of extraction of iron ore from large open-pit or shaft mining operations. The raw ore is then refined through a process where it is mechanically treated to remove impurities, and converted to pellets or sinter typically through the addition of bentonite. In the virgin steel manufacturing process, agglomerated iron ore is combined with coke and limestone to form a charge material that enters a blast furnace where the iron ore is reduced to produce pig iron. The next step in the

manufacturing process uses a basic oxygen furnace (BOF) to produce steel from a mixture of molten pig iron and scrap metal. As a result, even “virgin” steel contains a small amount of recycled metal (and the values reported for virgin steel production represent extrapolated estimates of energy intensity of a theoretical production process with 100% virgin inputs). The raw steel is then milled and rolled to produce a sheet material that then undergoes a series of stamping and welding processes to fabricate steel products (e.g., cans). Data was not found on the energy associated with different fabrication steps (for either virgin or recycled steel).

While some recycled material is consumed through the BOF process, the electric arc furnace (EAF) produces recycled steel from a feedstock that is almost 100 percent recycled metal. The EAF operates with a charge (inputs) that consists of scrap material typically combined with a small amount of coke and limestone. In the EAF, heat is applied to the scrap metal charge through electric current passed between carbon electrodes to produce molten steel (EPA 2002).

In both the BOF and EAF processes, the coke that is consumed performs a dual role, both as an energy source and as a metallurgical ingredient in the alloy. In our calculations, coke is accounted for as an energy input.

There are non-energy CO₂ emissions associated with (1) consumption of limestone in both the virgin and recycled processes and (2) the carbon anode in the EAF (recycled) process. The former is incorporated in the life cycle, but the latter emissions were not explicitly quantified. Process non-energy emissions associated with limestone consumption in the steel manufacturing process were estimated to be 0.043 Tonne eCO₂/Tonne (Timler 2002; EC 2001).¹⁴

Partial life-cycle emissions estimates for steel were based on data from large integrated mills in Ontario that produce steel from iron ore, and for the electric mills distributed across the country that produce steel from recycled scrap. This expanded life cycle for steel includes energy associated with the extraction of inputs used in the production of steel sheet. The current data set also includes raw materials acquisition for the recycled process (i.e., adding the emissions associated with separating steel from other materials at a Materials Recovery Facility) and a rough estimate of transportation emissions, although these factors have a relatively small influence on overall emissions. Steel is estimated to contain 86 percent virgin content on average¹⁵, and the post-consumer recycling retention rate is 79 percent (Enviros RIS 2000). Exhibit B-13 and Exhibit B-14 show the complete life-cycle energy data associated with the raw materials acquisition, manufacturing, and transportation of steel.

¹⁴ Note that these emissions include the CO₂ liberated in conversion of CaCO₃ to CaO, but not the energy required for the process.

¹⁵ As with aluminum, the recycled content of steel does not affect its physical properties or economic value.

The net GHG emission factors for the various waste management options for steel¹⁶ are shown in Exhibit 3-3, and their derivation is discussed below.

Exhibit 3-3. GHG Emissions from Waste Management Options for Steel (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE)
Steel	(1.18)	0.01	(1.03)	0.01

3.2.1 RECYCLING

Recycling steel provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials. The GHG emission benefits of recycling steel are presented in Exhibit 3-4.

Exhibit 3-4. Recycling Emissions for Steel (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Waste Management Option	Process Energy	Transportation Energy	Process Non-Energy	Net Emission Factor (=a + b + c)
Recycling	(1.13)	(0.01)	0.03	(1.18)

3.2.1.1 Raw Materials Acquisition

Virgin Product: Estimates for the energy associated with raw materials acquisition of steel were based on the Athena Institute report (Athena Institute 1998). Athena provided fuel-specific raw materials acquisition estimates for one square meter of residential steel cladding, which represents 3.8 kg of steel. These values were then converted to GJ per kg of steel, as shown in Exhibit B-15.

Recycled Product: Energy associated with the “raw materials acquisition” of steel made from recycled product refers to fuel and electricity consumed at materials recovery facilities (“MRFs”), where the usable portion of secondary steel (or more accurately, ferrous materials from the solid waste stream) is separated from other materials. To develop this estimate, a benchmark value of 0.6 kg eCO₂ per tonne of waste associated with energy use at waste

¹⁶ Please note that the raw material acquisition and manufacturing data examined in this report is specific to the production of steel. In the absence of better information, the emission factors presented in this section may be used as a surrogate for other ferrous (iron-containing) materials such as cast iron and stainless steel. Also note that when discussing steel from the perspective of the market for scrap materials, it is frequently referred to as ferrous material.

management facilities was used (Torrie Smith Associates 2003). In using this value, it was assumed that “waste management facilities” represent a reasonable surrogate for MRFs. After then assuming that the energy associated with these emissions is exclusively electricity, this estimate was converted to kilowatt-hours (kWh) of equivalent electricity, and subsequently into GJ of energy, as shown in Exhibit B-16.

3.2.1.2 Manufacturing and Fabrication

Energy data for manufacturing/fabrication are shown in Exhibit B-17 and Exhibit B-18 for virgin and recycled inputs, respectively. As noted in the original report, separate energy intensity figures were developed for production from the large integrated mills in Ontario that produce steel from iron ore and for the electric mills distributed across the country that produce steel from recycled scrap. The mini-mill energy intensities were then equated with production from recycled inputs and the blast furnace operations with production from virgin inputs. The contribution of the integrated blast furnace operations in Ontario to total production of steel in Canada varies with market conditions; it was assumed 50 percent of primary steel production is from these mills. The energy consumption of steel making was apportioned to the two different production technologies, with the integrated blast furnace operations being assigned 100 percent of the coal, 50 percent of the natural gas, 10 percent of electricity, and 90 percent of other fuel consumption (CIEEDAC 2000). This leads to a final energy intensity of steel-making of 22.8 GJ/tonne from virgin inputs (69 percent coal, 24 percent gas) and 9.3 GJ/tonne from recycled inputs (39 percent electricity, 59 percent gas). Although it is not entirely clear from the original data sources, our interpretation is that the manufacturing data set includes the energy associated with fabrication of steel sheet into final steel products (e.g., steel cans).

3.2.1.3 Transportation

Transportation estimates for steel production are shown in Exhibit B-19 and Exhibit B-20.

Raw Materials Acquisition (Virgin Production): The estimate of transportation energy associated with the raw materials acquisition of steel inputs (0.2 GJ/tonne) was obtained from the Athena Institute report (Athena Institute 1998). The Athena report cited an estimate of 828 KJ of diesel energy per one square meter of residential steel cladding, which represents 3.8 kg of steel.

Manufacturing and Fabrication (Virgin and Recycled Production): Due to the lack of readily-available transportation energy estimates for manufacturing and fabrication of steel products a rough approximation (0.07 GJ/tonne), was developed through the following steps: 1) assumed a typical distance of 100 km of truck transport per tonne during manufacturing and fabrication; 2) converted this estimate to litres of diesel fuel using an assumed fuel economy of 2.3 km per litre; 3) converted this fuel estimate to energy using data on the heat content of diesel; and 4) converted the resulting fuel intensity value to GHG emissions based on the carbon content of diesel fuel. This calculation is shown in Exhibit B-21.

Transport to End Use (Virgin and Recycled Production): The estimate for transporting steel products from the manufacturing plant to the market (0.3 GJ/tonne) was based on an estimated transportation distance of 426 km of truck transport to ship glass to the market (i.e., glass was used as a surrogate for steel), provided by the Athena Institute. This estimate was then converted

to the equivalent amount of GJ of diesel fuel using the same method as described above for “manufacturing and fabrication.” This calculation is shown in Exhibit B-22.

3.2.2 COMBUSTION

Most energy from waste (EFW) facilities recover the ferrous values (including steel) from their waste stream by passing the bottom ash through a magnetic separator. The steel and other ferrous materials thus separated are then sent to electric arc furnaces for recycling. An estimate of the recycling emission reduction for combustion was developed using the same assumptions as the U.S. EPA analysis (EPA 2002). Specifically, it was assumed that 90 percent of combustion facilities recover ferrous metals and that at those facilities, 98 percent of the ferrous metals are collected. These assumptions yield an overall recovery rate of 88 percent.

The overall recycling emission factor for steel was used, along with the recovery factor, to derive a recycling emission reduction estimate for combustion. Of the materials analyzed, this applies only to steel. As shown in Exhibit 3-5 the GHG emissions benefit of managing ferrous materials at EFW facilities is 0.99 tonnes eCO₂/tonne of ferrous inputs.

Exhibit 3-5. Combustion Emissions for Steel (tonnes eCO₂/tonne)

(a)	(b)	(c)	(d)	(e)
Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b + c + d)
0.00	0.01	0.00	(1.04)	(1.03)

3.2.3 LIMITATIONS

The complexity of the steel manufacturing and disposal/recycling system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent average Canadian conditions that may not accurately characterize national or site-specific conditions. For example, the manufacturing energy data represents the entire Canadian steel industry (CIEEDAC 2000). There is likely to be some variation between individual steel production facilities with respect to energy consumption efficiency and fuel type. Site-specific variability is also a concern with each of the end-of-life management options (e.g., landfill transport distances). In addition, these values do not address international cross-border flows. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with steel recycling, landfilling, and combustion activities from a national average perspective.

3.3 Copper Wire

The life cycle for virgin copper starts with the raw materials acquisition process, which consists of extraction of copper ore, usually sulfide or oxide based, from large open-pit or shaft mining operations. The raw ore is then refined through a process where it is crushed and then processed

through a ball or rod-milling machine. At this stage the two types of ores undergo different refining and processing stages. These stages are pyrometallurgical, or smelting and hydrometallurgical, or leach-solvent extraction-electrowinning (SX/EW) process. Because copper production in Canada is primarily through the more common smelting process, the SX/EW manufacturing process will not be discussed in detail. Once the copper ore has been milled, it is mixed with water to create a slurry where copper is recovered and concentrated through a flotation process. Chemicals are added during this process that coat the copper minerals and allow for air bubbles to carry them to the surface of the tank where they are collected through a skimming process and allowed to dry. Waste slag or tailings are typically collected and disposed or reprocessed to recover other materials. The collected copper concentrate now contains about 30 percent copper. The copper concentrate then undergoes a smelting process where it is fed through a series of furnaces to remove non-copper minerals and other contaminants. The copper concentrate results in successive production of matte, blister, and eventually 99 percent pure copper that is formed into molds called anodes. These anodes then undergo electrolytic refining in an acid bath to produce 99.99 percent pure copper cathode. At this point the manufacturing process typically becomes specific to the desired use of the copper material where the cathode is formed into a secondary shape through remelting in a reverberatory furnace. For copper wire, the copper cathode is formed into wire rod about ½" in diameter that is then drawn through a series of dies to produce copper wire of varying gauges, or thickness. For other applications the copper cathode can be formed into billets, slabs or ingots, which can be extruded, cast, or alloyed. Due to purity constraints, most electrical copper wire is produced from virgin copper cathode.

Secondary copper wire is typically recovered under two basic classifications, Number 1 and Number 2. No. 1 copper scrap consists of unalloyed copper that is clean and free of contaminants. No. 2 copper scrap consists of unalloyed copper with a minimum of 94 percent purity, and may have some contamination in the form of plastics or other metals. Copper wire scrap is typically chopped and processed to remove insulation and other contaminants. Incineration is also used in some cases to remove insulation from copper wire, but significant air pollution issues limit the use of this wire preparation method. After chopping, the "clean" copper wire is then remelted in a reverberatory furnace and cast into ingot. Because No. 2 scrap is less pure, it typically must undergo anode and electrolytic refining before entering the cathode remelting stage. Thus, the processing of No. 2 scrap requires more energy than No. 1 scrap. The recovered copper wire typically goes into billets or ingots for alloying or other grades of copper with lesser purity constraints than electrical copper wire.

This life cycle for copper wire includes energy associated with the extraction of raw materials used in the production of copper wire. The current data set also includes raw materials acquisition for the recycled process (i.e., adding the emissions associated with processing the copper wire before remelting) and a rough estimate of transportation emissions, although these factors have a relatively small influence on overall emissions. Copper wire's post-consumer recycling retention rate is 82 percent (FAL 2002). Exhibit B-23 and Exhibit B-24 in Appendix B show the complete life-cycle energy data associated with the raw materials acquisition, manufacturing/fabrication, and transportation of copper wire. The net GHG emission factors for the various waste management options for copper wire are shown in Exhibit 3-6, and their derivation is discussed below.

Exhibit 3-6. GHG Emissions from Waste Management Options for Copper Wire (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE)
Copper Wire	(4.10)	0.01	0.01	0.01

3.3.1 RECYCLING

Recycling copper wire provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials. The GHG emission impacts of recycling copper wire are presented in Exhibit 3-7.

Exhibit 3-7. Recycling Emissions for Copper Wire (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Waste Management Option	Process Energy	Transportation Energy	Process Non-Energy	Net Emission Factor (= a + b + c)
Recycling	(4.03)	(0.06)	0.00	(4.10)

3.3.1.1 Raw Materials Acquisition

Virgin Product: The estimate for the energy associated with raw materials acquisition of copper wire was based on the Franklin Associates report, *Energy and Greenhouse Gas Factors for Personal Computers* (FAL 2002). Franklin Associates provided fuel-specific raw materials acquisition estimates for the production of copper wire utilized as a component of personal computers. These values were then converted to GJ per tonne of copper wire, and assumed that Canadian production has the same energy intensity and fuel mix as the U.S. production values reported by Franklin Associates.

Recycled Product: Energy associated with the “raw materials acquisition” of copper made from recycled product refers to fuel and electricity consumed at facilities where copper wire scrap is shredded and prepared for the remelting process. Data were obtained from the report, *Energy Use Patterns for Metal Recycling*, prepared by the U.S. Bureau of Mines (Kusik and Kenahan 1978). Although this report is quite dated, it continues to be cited in the literature as a source of information on copper industry energy.

3.3.1.2 Manufacturing and Fabrication

Energy data for manufacturing/fabrication of virgin copper wire is in Exhibit B-17. Data from FAL (2002) aggregates the raw materials acquisition, manufacturing and fabrication steps for a total of 78.2 GJ/tonne of virgin copper wire. The energy intensity of manufacturing/fabricating secondary copper ingot from recycled copper wire is 6.7 GJ/tonne and is detailed in Exhibit B-

18. Data obtained from Kusik and Kenahan (1978) was used, and again assumed that U.S. energy intensity and fuel mix apply to Canada (and that 1978 data applies to current conditions). Because recovered copper wire is usually used to produce material not used for copper wire production (i.e. open loop recycling), it was assumed that the displacement of virgin copper ingot has an estimated total energy value of 67.2 GJ/tonne, based on a somewhat dated U.S. study (Battelle 1975). As a result, the GHG emission benefits for recycle copper wire are based on an assumed displacement of the production of virgin copper ingot. Based on foundry location and capacity, Ontario accounts for 52 percent of copper smelting capacity in Canada, with Quebec and Manitoba accounting for 33 and 15 percent, respectively.

3.3.1.3 Transportation

Raw Materials Acquisition (Virgin Production): The estimate of transportation energy associated with the raw materials acquisition of copper wire was obtained from the Franklin Associates personal computer life-cycle report. Data on virgin production transportation was obtained from the report, *Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4)*, Battelle (1975). This energy was aggregated with energy associated with manufacturing and fabrication for both of these materials.

Manufacturing and Fabrication (Virgin and Recycled Production): As noted above, the manufacturing and fabrication energy associated with manufacturing copper wire was aggregated for a total of 0.6 GJ/tonne as shown in Exhibit B-23. The total transportation energy for manufacturing virgin ingot is 2.37 GJ/tonne. Transportation data for the manufacturing/fabrication of secondary copper ingot from recycled copper wire is 1.84 GJ/tonne and is detailed in Exhibit B-24. Data obtained from Kusik and Kenahan (1978) was used.

3.3.2 COMBUSTION

Information on the combustion of copper wire was not readily available. For the sake of developing a rough estimate, the average of the existing combustion energy factors for aluminum and steel cans (without the steel recovery energy benefit) were applied. This value is 0.09 GJ/tonne combusted. The only source of GHG emissions associated with the combustion of copper wire is the energy required to transport the material to the combustion facility. As shown in Exhibit 3-8 the net GHG emissions of combusting copper wire at these facilities is 0.01 tonnes eCO₂/ton.

Exhibit 3-8. Combustion Emissions for Copper (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Waste Management Option	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b + c + d)
Combustion	0.00	0.01	0.00	0.00	0.01

3.3.3 LIMITATIONS

The complexity of the copper wire manufacturing and disposal/recycling system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent conditions in the United States that may not accurately characterize national or site-specific conditions. For example, the raw material acquisition and manufacturing energy data is based on copper manufacturing data from the United States (Kusik and Kenahan 1978; Battelle 1975). There is likely to be some variation between individual copper production facilities with respect to energy consumption efficiency and fuel type. While this data is somewhat dated, it is still cited frequently in industry publications. Copper production characteristics within Canada are unlikely to differ significantly from those in the United States. Site-specific variability is also a concern with each of the end-of-life management options (e.g., landfill transport distances). In addition, these values do not address international cross-border flows. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with copper wire recycling, landfilling, and combustion activities from a national average perspective.

3.4 Glass

According to the Canadian Museum of Civilization, glass-making was first practiced over 5,000 years ago, and its history in Canada dates to the 1800s (CMC 2005). The principal ingredients are sand, crushed quartz, soda ash, lime, and cullet (broken glass), and the raw material acquisition step consists of mining and processing these materials. The presence of cullet in the mix accelerates the melting and crystallization of the other ingredients. Thus, as a practical matter, there are no 100% “virgin” glass processes in operation, nor are there 100% recycled processes, because all glass production uses some recycled and some virgin inputs. In general, the higher the recycled content of the mix, the lower the melting point, and the less energy required to heat the furnaces. The fabrication of glass into bottles and other products occurs at the point of manufacture.

Life-cycle emissions estimates for glass bottles were developed based on an assumed 6 GJ/tonne for production from virgin inputs and 4.25 GJ/tonne for production from recycled glass bottles (Torrie Smith Associates 2001). The life cycle for glass bottles were expanded by including energy associated with acquiring raw materials used in glass manufacturing. Also included was raw materials acquisition for the recycled process (i.e., adding the emissions associated with separating glass from other materials at a Materials Recovery Facility) and a rough estimate of transportation emissions, although these factors have a relatively small influence on overall emissions. Glass is estimated to contain 70 percent virgin content on average, and the post-consumer recycling retention rate is 71 percent (Enviros RIS 2000). Exhibit B-25 and Exhibit B-26 show the life-cycle energy data associated with the raw materials acquisition, manufacturing/fabrication, and transportation of glass bottles.

The net GHG emission factors for the various waste management options for glass bottles are shown in Exhibit 3-9, and their derivation is discussed below.

Exhibit 3-9. GHG Emissions from Waste Management Options for Glass (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE) - National Average
Glass	(0.10)	0.01	0.01	0.01

3.4.1 RECYCLING

Recycling glass bottles provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials. The GHG emission impacts of recycling glass bottles are presented in Exhibit 3-10.

Exhibit 3-10. Recycling Emissions for Glass Bottles (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Waste Management Option	Process Energy	Transportation Energy	Process Non-Energy	Net Emission Factor (=a + b + c)
Recycling	(0.12)	0.01	0.00	(0.10)

3.4.1.1 Raw Materials Acquisition

Virgin Product: Estimates of the energy associated with raw materials acquisition of glass bottles were based on data from Natural Resources Canada’s Comprehensive Energy Use Database (NRCan 2004). Table 15 of the database provides secondary energy consumption (by fuel) and production tonnages for “Other Non-Metal Mines.” These values were used to calculate the energy intensity and fuel use for the sand and limestone that serve as inputs to glass

manufacturing.¹⁷ To estimate GJ per ton, each of the fuel-specific energy consumption estimates for 2001 were divided by the total production estimate in 2001 (expressed in PJ), and converted to GJ. This calculation is shown in Exhibit B-27.

Recycled Product: Energy associated with the “raw materials acquisition” of glass made from recycled product refers to fuel and electricity consumed at materials recovery facilities (“MRFs”), where the usable portion of secondary glass is isolated from other materials. To develop this estimate, a benchmark value of 0.6 kg eCO₂ per tonne of waste associated with energy use at waste management facilities was used (Torrie Smith Associates 2003). In using this value, it was assumed that “waste management facilities” represent a reasonable surrogate for MRFs. After then assuming that the energy associated with these emissions is exclusively electricity, this estimate was converted to kWh of equivalent electricity, and subsequently into GJ of energy, as shown in Exhibit B-16.

3.4.1.2 Manufacturing and Fabrication

Energy data for manufacturing/fabrication are shown in Exhibit B-17 and Exhibit B-18 for virgin and recycled inputs, respectively. Initially it was 6 GJ/tonne was assumed for the production from virgin inputs and 4.25 GJ/tonne for production from recycled glass bottles, with natural gas providing 85-90 percent of this energy. These values represent extrapolated estimates of energy intensity of theoretical production processes with 100 percent virgin inputs and 100 percent recycled inputs; in reality, all production has some virgin and some recycled inputs. For this report, it was assumed that these estimates capture the energy associated with fabrication into individual glass bottles.

3.4.1.3 Transportation

Transportation estimates for glass production are shown in Exhibit B-19 and Exhibit B-20.

Raw Materials Acquisition (Virgin Production): Estimates of transportation associated with the raw materials acquisition of glass inputs (0.6 GJ/tonne) were based on data for steel, as provided in the Athena Institute report (Athena Institute 1998). This estimate can likely be improved with better data, however due to the relatively small contribution of this component to the total life-cycle energy for glass, steel was assumed to be a reasonable surrogate.

Manufacturing and Fabrication (Virgin and Recycled Production): Due to the lack of readily-available transportation energy estimates for manufacturing and fabrication of glass products, this estimate (0.07 GJ per tonne) was developed through the following steps: 1) assumed a typical distance of 100 km of truck transport per tonne during manufacturing and fabrication; 2) converted this estimate to litres of diesel fuel using an assumed fuel economy of 2.3 km per litre; 3) converted this fuel estimate to energy using This calculation is shown in Exhibit B-21.

¹⁷ Soda ash, which is another input in glass production, is not included in this analysis. It may have a significant effect on total energy use, and should be considered for inclusion in future improvements to the data set.

Transport to End Use (Virgin and Recycled Production): The estimate for transporting glass products from the manufacturing plant to the market (0.3 GJ/tonne) was based on an estimated average transportation distance of 426 km of truck transport, provided by the Athena Institute (Athena 1998). This estimate was then converted to the equivalent amount of GJ of diesel using the same method as described above in “manufacturing and fabrication.” This calculation is shown in Exhibit B-22.

3.4.2 COMBUSTION

The only source of GHG emissions associated with the combustion of glass bottles is the energy required to transport the material to the combustion facility. As shown in Exhibit 3-11 the net GHG emissions for glass bottles at these facilities is 0.01 tonnes eCO₂/ton.

Exhibit 3-11. Combustion Emissions for Glass Bottles (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Waste Management Option	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b + c + d)
Combustion	0.00	0.01	0.00	0.00	0.01

3.4.3 LIMITATIONS

The complexity of the glass manufacturing and disposal/recycling system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent average conditions that may not accurately characterize national or site-specific conditions. For example, the raw material acquisition and manufacturing energy data is based on Canadian glass industry data (Torrie Smith Associates, 2001). There is likely to be some variation between individual glass production facilities with respect to energy consumption efficiency and fuel type. Site-specific variability is also a concern with each of the end-of-life management options (e.g., landfill transport distances). In addition, these values do not address international cross-border flows. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with glass recycling, landfilling, and combustion activities from a national average perspective.

4 Plastics & Tires

This section provides details on the development of emission factors for plastics and tires. These materials are grouped together in this section because they all share relatively similar and energy intensive upstream processes, including petroleum acquisition, refining, and forming. These materials are also inert (from a waste disposal GHG emission perspective); therefore, none of these materials contributes to downstream emissions associated with the decomposition of organic material. These materials are non-reactive in a landfill environment, and the only energy associated with this disposal option for these materials is 0.15 GJ/tonne for waste collection vehicles, transport to the landfill, and heavy equipment operation at the landfill. These materials are also non-reactive in an anaerobic digester, and the energy associated with this end-of-life option for these materials is 0.11 GJ/tonne for collection vehicles and transport to the digestion facility. Plastics and tires are typically not composted due to their inertness and interference with the compost turning/aeration process. Thus, anaerobic digestion, or composting are not discussed in the remainder of this chapter.

The following sections provide details on the energy associated with recycling, and combustion of plastics and tires.

4.1 HDPE, PET, and Other plastic packaging

Life cycles were developed for three grades of plastic: high-density polyethylene (HDPE), bottle grade polyethylene terephthalate (PET), and linear low-density polyethylene (LLDPE). The values for LLDPE were used to represent “other plastic” in the analysis, as industry sources suggest that this product contributes the largest quantity of recycled plastic that is neither HDPE nor PET. Although additional information on plastics from a variety of sources was researched, the most complete information was contained in the data set used in the initial report, which was provided by the Canadian Plastics Industry Association (CPIA 2001).

The stages in the life cycle are similar for all three types of plastic. The life cycle for virgin HDPE and LLDPE includes extraction and processing of crude oil and natural gas (raw material acquisition); production of ethylene, polymerization, and pelletization (manufacturing); and shipment to a fabrication facility where the pellets are melted and extruded or formed into a final product (EPA 2002). The virgin PET life cycle differs slightly in that the manufacturing step also includes conversion of ethylene to ethylene glycol, and production of terephthalic acid (TPA) and dimethylterephthalate (DMT) (these steps contribute to the higher manufacturing energy intensity of PET compared to HDPE and LLDPE).

For all three plastics, the stages in the production of recycled materials are plastic resin separation by mechanical stripping or manual separation from other recyclables (raw material acquisition); cleaning, drying, extruding, and pelletizing (manufacturing); and shipment to a fabrication facility where the pellets are melted and extruded or formed into a final product (EPA 2002).

The principal expansion of the life cycle for the plastics in this report is that the current data set includes the energy (and emissions) associated with producing the feedstock for virgin plastics production (i.e., raw materials acquisition). The current data set also includes raw materials acquisition for the recycled process (i.e., adding the emissions associated with separating plastics from other materials at a Materials Recovery Facility) and a rough estimate of transportation emissions, although these factors have a small influence on overall emissions. HDPE and PET are estimated to contain 85 and 71 percent virgin content, respectively, and the post-consumer recycling retention rate is 86 percent for both (Enviros RIS 2000). Exhibit B-28 through Exhibit B-33 show the complete life-cycle energy data associated with the raw materials acquisition, manufacturing/fabrication, and transportation of plastics. The net GHG emission factors for the various waste management options for plastics are shown in Exhibit 4-1, and their derivation is discussed below.

Exhibit 4-1. GHG Emissions from Waste Management Options for HDPE, PET, Other Plastics, and Tires (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions
HDPE	(2.27)	0.01	2.89	0.01
PET	(3.63)	0.01	2.17	0.01
Other Plastic	(1.80)	0.01	2.67	0.01

4.1.1 RECYCLING

Recycling HDPE, PET, and Other Plastic provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials. The GHG emission impacts of recycling HDPE, PET, and Other Plastic are presented in Exhibit 4-2.

Exhibit 4-2. Recycling Emissions for HDPE, PET, and Other Plastic (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Material Type	Process Energy	Transportation Energy	Process Non-Energy	Net Emission Factor (=a + b + c)
HDPE	(2.26)	(0.02)	0.00	(2.27)
PET	(3.61)	(0.02)	0.00	(3.63)
Other Plastic	(1.79)	(0.01)	0.00	(1.80)

4.1.1.1 Raw Materials Acquisition

Exhibit B-34, Exhibit B-35, and Exhibit B-36 show the energy data associated with the raw materials acquisition of HDPE, PET, and “other” plastic (LLDPE), respectively.

Virgin Product: One of the conventions in life-cycle analysis, when applied to petroleum products such as plastics, synthetic rubber and the like, is to include the “embodied” energy when tallying energy inputs. This embodied energy represents the chemical bond energy of the

feedstock, and the original data set included information on the feedstock energy. For purposes of a GHG analysis, this energy is not directly relevant, as it would only translate into a GHG emission if the products were burned (and our analysis does include CO₂ emissions from plastics combustion).

However, the feedstock energy can be used to infer the GHG emissions associated with the raw materials acquisition step. Natural gas and petroleum can be used for both fuel and non-fuel (plastics, rubber, asphalt, lubricating oils, etc.) applications. As described in the next section of this appendix (“Pre-combustion”), estimates of the emissions associated with producing natural gas and refined petroleum products as fuels were developed. These estimates, expressed in terms of kg eCO₂ per GJ of *output* from the natural gas and refined petroleum product (RPP) industries, can be used to reflect the “upstream” (i.e., raw material acquisition and manufacturing) emissions for not only the fuel uses of fossil carbon, but also the non-fuel uses.

For purposes of estimating the GHG emissions for raw material acquisition and manufacturing of plastics, the feedstock energy (per GJ of *input* to the plastics manufacturing process) was multiplied by the pre-combustion emissions (per GJ of *output* from the natural gas and RPP industries). Details of the pre-combustion calculations are provided below. For these calculations, “oil” corresponds to RPP, and “other fuels” are assumed to be entirely natural gas.

Recycled Product: Energy associated with the “raw materials acquisition” of plastics made from recycled product refers to fuel and electricity consumed at materials recovery facilities (“MRFs”), where the usable portion of secondary plastic is isolated from other materials. To develop this estimate, a benchmark value of 0.6 kg eCO₂ per tonne of waste associated with energy use at waste management facilities (Torrie Smith Associates 2003) was used. In using this value, it was assumed that “waste management facilities” represent a reasonable surrogate for MRFs. After then assuming that the energy associated with these emissions is exclusively electricity, this estimate was converted to kWh of equivalent electricity, and subsequently into GJ of energy, as shown in Exhibit B-16.

4.1.1.2 Manufacturing and Fabrication

Energy data for manufacturing/fabrication are shown in Exhibit B-17 and Exhibit B-18 for virgin and recycled inputs, respectively. The estimates of energy intensity and fuel mix for the virgin processes reflect the production of ethylene, polymerization, and pelletization steps (and for PET, production of TPA and DMT), and as mentioned previously, are based on data provided by CPIA (CPIA 2001). Although there are few sources of data that specify energy required to produce plastic from recycled material, data from recycling facilities in Ontario indicate that it takes 6 GJ/tonne of energy to prepare a recovered plastic for use again. Of this energy, approximately 75 percent is electricity, with the energy required to grind, wash, dry, and reform the plastic into pellets.

4.1.1.3 Transportation

No Canadian data were readily available on transportation associated with plastic production. Consequently, the transportation estimates were based on the following, as shown in Exhibit B-19 and Exhibit B-20.

Raw Materials Acquisition (Virgin Production): Our estimates of transportation associated with the raw materials acquisition of plastic inputs (0.6 GJ/tonne) were based on data for steel, as provided in the Athena Institute report (Athena Institute 1998). This estimate can likely be improved with better data, especially since much of the raw material transportation for plastics is via pipeline, as opposed to rail, barge, and truck as for steel. Nonetheless, due to the relatively small contribution of this component to the total life-cycle energy for plastics, steel was assumed to be a reasonable surrogate.

Manufacturing and Fabrication (Virgin and Recycled Production): Due to the lack of readily-available transportation energy estimates for manufacturing and fabrication of plastic products, a rough estimate (0.07 GJ/tonne) was developed through the following steps: 1) assumed that 100 km of truck transport for a tonne of plastic during manufacturing and fabrication; 2) converted this estimate to litres of diesel fuel using an assumed fuel economy of 2.3 km per litre; 3) converted this fuel estimate to energy using data on the heat content of diesel. This calculation is shown in Exhibit B-21.

Transport to End Use (Virgin and Recycled Production): The estimate for transporting plastic products from the manufacturing plant to the market (0.3 GJ/tonne) was based on an estimated transportation distance of 426 km of truck transport to ship glass to the market (i.e., glass as a surrogate for plastics was used), provided by the Athena Institute. This estimate was then converted to the equivalent amount of GJ of diesel fuel using the same method as described above for “manufacturing and fabrication.” This calculation is shown in Exhibit B-22.

4.1.2 COMBUSTION

The combustion of plastics typically results in a release of the embedded petroleum energy within the incinerator, and produces some energy and GHG emissions displacement in conjunction with electricity generation capacity. There is however a significant release of CO₂ from the combustion of plastics along with transportation related energy. Exhibit 4-3 provides details on GHG emission components associated with plastic combustion.

Exhibit 4-3. Combustion Emissions for HDPE, PET, and Other Plastic (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Material Type	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b + c + d)
HDPE	3.12	0.01	(0.24)	0.00	2.89
PET	2.28	0.01	(0.12)	0.00	2.17
Other Plastic	2.84	0.01	(0.18)	0.00	2.67

4.1.3 LIMITATIONS

The complexity of the plastic manufacturing and disposal/recycling system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent average conditions that may not

accurately characterize national or site-specific conditions. For example, the raw material acquisition and manufacturing energy data is based on Canadian plastic industry data on a national scale (CPIA 2001). There is likely to be some variation between individual plastic production facilities with respect to energy consumption efficiency and fuel type. Site-specific variability is also a concern with each of the end-of-life management options (e.g., combustion transport distances). In addition, these values do not address international cross-border flows. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with plastics recycling, landfilling, and combustion activities from a national average perspective.

4.2 Tires

Tires have long been viewed as “problem materials” by waste managers. There have been many reports of difficulty handling and compacting tires in landfills. More dramatically, when the tires have been collected in separate piles, there have been several incidents where these piles caught fire and have been very difficult to extinguish, in some cases burning for months.

In response to these problems, many public and private sector waste managers have adopted programs to divert tires from disposal. Used tires are destined for a variety of fates. Provided that the core of a used tire is in good shape, re-treading is an option (and in this case, the tire is not considered to be a “scrap” tire). Other fates include remanufacture into molded products (such as blasting mats for demolition applications), use as an ingredient to crumb rubber modified (CRM) asphalt, shredding for use in civil engineering applications, baling and storage, and use as tire-derived fuel (TDF).

NRCan has been collecting information on the distribution of scrap tire use by province, as shown in Exhibit 4-4 below (Pehlken 2005). Although all of the scrap tire management techniques may have effects on GHG emissions, given the time and resource constraints for this project, data was only collected on re-treading, use as TDF, and landfilling.

Exhibit 4-4. Annual scrap tire usage by province

Province	Tire Usage in metric tonnes					
	Molded Products	Crumb	Shred	Tire Derived Fuel	Baled / Stored	Total
Alberta	4,869	8,379	15,245	0	0	28,493
British Columbia	23,003	0	0	5,344	0	28,346
Manitoba	1,889	0	8,706	1,505	0	12,099
New Brunswick	6,319	98	0	0	0	6,417
Newfoundland and Labrador	0	0	0	0	3,280	3,280
Nova Scotia	0	5,235	0	0	0	5,235
Ontario	6,560	43,337	6,560	30,520	8,200	95,177
Prince Edward Island	0	0	0	0	1,577	1,577
Quebec	0	43,358	0	11,525	0	54,883
Saskatchewan	120	6,342	718	0	0	7,179
Canada	42,759	106,748	31,229	48,894	13,057	242,687

Source: Unpublished data assembled by Alexandra Pehlken, NRCan

The net GHG emission factors for the various waste management options for tires are shown in Exhibit 4-5, and their derivation is discussed below.

Exhibit 4-5. GHG Emissions from Waste Management Options for Tires (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE) - National Average
Tires	(3.29)	0.01	(0.49)	0.01

4.2.1 RECYCLING

Recycling tires provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials. The GHG emission impacts of recycling tires are presented in Exhibit 4-6.

Exhibit 4-6. Recycling Emissions for Tires (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Waste Management Option	Process Energy	Transportation Energy	Process Non-Energy	Net Emission Factor (=a + b + c)
Recycling	(3.29)	NA	NA	(3.29)

4.2.1.1 Raw Materials Acquisition, Manufacturing and Fabrication, and Transportation

Unlike most of the other materials covered in this report, full life-cycle emissions on raw material acquisition and manufacturing were not collected, so an abbreviated life cycle was characterized, using several simplifying assumptions, as discussed below.

According to a study of energy and GHG implications of scrap tire management in Australia (Atech Group 2001), the average energy required to produce a new tire is 974 MJ, and the energy to produce a retread is 400 MJ. The life-cycle boundaries for these estimates are not stated in the study, so it is not clear whether raw material acquisition or transportation is included. The following series of assumptions were made:

- The energy intensity for tire production in Canada is similar to that in Australia
- The fuel mix for new tires and retreads is the same, and can be approximated by the fuel mix reported for the rubber industry (CIEEDAC, 2005).
- The reported energy values pertain to passenger tires, which are assumed to have an average weight of 9.5 kg per new (or retreaded) tire (Atech Group 2001).
- The effect of loss rates and the difference in mass (of a scrap tire compared to a new tire) are accounted for in the energy intensity values.
- The energy intensity and fuel mix required for passenger tire production is the same on a per tonne basis as for truck and off-road vehicle tires.
- A retreaded tire has 75 percent of the use life of a new tire, and thus from a functional equivalence standpoint, the energy savings associated with producing a retread tire compared to a new tire should be counterbalanced by the shorter lifespan (Atech Group 2001).

Combining these assumptions, the GHG emission reduction associated with recycling (i.e., retreading) 1 tonne of tires is about 3.29 tonnes eCO₂ as shown in the exhibit above.

4.2.2 COMBUSTION

There are three cement kilns (two in Quebec and one in BC) and one paper mill in BC using tires as TDF (Pehlken 2005). Burning tires in municipal waste combustors is not believed to be a significant activity in Canada.

At the cement kilns where TDF is used, it substitutes for coal. Cement kilns can use other fuels (particularly natural gas), but the calculations reported here are based on the assumption that the appropriate basis for comparison is the carbon content per unit energy for TDF compared to coal. It was also assumed that the transportation energy for coal and TDF are equal.

The Australian tire study (Atech Group 2001) reports that the energy content per passenger tire is about 260 MJ, and that the carbon content per unit energy (carbon coefficient) is 75 kg eCO₂/GJ. Again assuming an average tire weight of 9.5 kg, this implies that for every tonne of TDF combusted, 27 GJ of energy is yielded, and 2.05 kg eCO₂ is emitted. If enough coal is burned to yield 27 GJ, about 2.55 kg eCO₂ is emitted. Thus, the GHG emission reductions of burning TDF in lieu of coal are 0.50 kg eCO₂/tonne. This analysis suggests that from a climate change perspective only, it would be better to use tires as fuel than coal.

An emission factor was not developed for use of TDF in paper mills. However, our understanding is that at the paper mill in BC currently using TDF, the TDF displaces natural gas and allows greater use of biomass fuels during winter months, when the biomass fuel quality is lower (Pehlken 2005). Reportedly the GHG effect is about neutral. As shown in Exhibit 4-7, the GHG emissions benefits of burning TDF in lieu of other fuels is 0.49 tonnes eCO₂/ton.

Exhibit 4-7. Combustion Emissions for Tires in Cement Kilns (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Waste Management Option	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b + c + d)
Combustion	(0.50)	0.01	NA	NA	(0.49)

4.2.3 LIMITATIONS

The complexity of the tire manufacturing and disposal/recycling system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent conditions that may not accurately characterize national or site-specific conditions. For example, the raw material acquisition and manufacturing energy data is based on an Australian tire industry study (Atech Group 2001) that is believed to be representative of standard industry practices also used in Canada. There is likely to be some variation between individual tire production and retreading facilities in Canada with respect to energy consumption efficiency and fuels used. Site-specific variability is also a concern with each of the end-of-life management options (e.g., combustion transport distances).

In addition, these values do not address international cross-border flows. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with tire recycling, landfilling, and combustion activities from a national average perspective.

5 Forest Products

Forest products – paper and wood – make up a large proportion of the municipal waste stream as well as the construction and demolition waste stream. The scope of forest products covered by this report is limited to four of the most common paper grades – newsprint, fine paper, cardboard, and other paper.

From a GHG perspective, paper has a more complex life cycle than the inorganic materials covered in earlier chapters. In addition to the energy-related GHG flows that dominate the emissions profile for inorganics, waste management options for paper can affect forest carbon stocks, landfill CH₄ emissions, and landfill carbon stocks. As discussed in Section 2.2.1.5 (Carbon sinks – forest carbon), increases in recycling would reduce the rate of pulpwood harvesting, thereby affecting the mass of carbon stored in Canada’s forests (the forest carbon discussion is not repeated in this chapter). Landfilling has two countervailing effects – the anaerobic situation results in CH₄ emissions, but it also results in long-term storage of that portion of the disposed carbon that does not readily degrade. The GHG profile for paper is also complicated by the fact that much of the paper that is diverted from disposal undergoes “open loop” recycling, in which the second generation product differs from the original product.

The GHG emission factors for the various waste management options for forest products are shown in Exhibit 5-1, and their derivation is discussed below.

Exhibit 5-1. GHG Emissions from Waste Management Options for Newsprint, Fine Paper, Cardboard, and Other Paper (tonnes eCO₂/tonne)

Material Type	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE) - National Average
Newsprint	(2.75)	(0.49)	(0.05)	(1.22)
Fine Paper	(3.20)	(0.34)	(0.04)	1.18
Cardboard	(3.26)	(0.32)	(0.04)	0.29
Other Paper	(3.27)	(0.23)	(0.04)	0.71

5.1 Newsprint, Fine Paper, Cardboard, Other Paper

The stages in the life cycle are similar for all four types of paper. In the virgin paper processes, the raw materials acquisition stage includes pulpwood harvesting, in which trees are typically cut

down using a chain saw, dragged by a tractor to a truck road, cut into transportable sized logs, and then loaded onto a truck¹⁸. The manufacturing step for paper consists of debarking (via dry friction, wet friction, or hydraulic debarking); chipping (using a rotating flywheel); and pulping. During pulping, individual cell components are separated such that they can later be reformed in a mat formation. For higher-grade paper types, including fine paper, paperboard, and “other” paper, a chemical pulping process is used. During chemical pulping, the lignin that binds the fibers together is dissolved chemically. In kraft pulping, wood chips are “cooked” in a digester at high temperature and pressure in a white liquor. For virgin newsprint, a thermomechanical pulping process separates wood fibers by mechanical means, resulting in a low grade fiber. For all paper types, after pulping, a multi-stage bleaching process takes place, during which the brightness and strength of pulps is enhanced. The pulp is then converted into sheets of paper and paperboard during the forming stage, where a web of fiber is formed from a fiber/water suspension of a paper machine wire; water is pressed out of the web; and water is driven off by heat. Finally, fabrication of paper products consists of scraping the paper off the dryer and winding it onto a bulk size reel (rolling), at which point the paper can be processed (e.g., cut) for final use.

For all four paper types, the stages in the production of recycled materials are separation from other recyclables (raw material acquisition); repulping through mixing with heated water; deinking in an alkaline solution; cleaning, screening, and washing, where contaminants are removed in a centrifugal cleaning system; sheet formation and drying (using the same process as was used in virgin production); and rolling/final processing (EPA 2002).

The life-cycle emissions estimates for each of the four grades of paper (newsprint, fine paper, cardboard, and “other” paper) includes energy-related CO₂ emissions at several steps: raw material acquisition (for virgin pulp, energy associated with harvesting pulpwood used in paper manufacturing; for the recycled process, the emissions associated with separating paper from other materials at a Materials Recovery Facility), manufacturing, and transportation. Please see Exhibit B-4 and Exhibit B-5 for details on retention rates and current mix values. Exhibit B-39 through Exhibit B-46 show the complete life-cycle energy data associated with these steps.

¹⁸ In addition to the biomass inputs to paper production, some papers also have substantial mineral inputs such as clay or calcium carbonate. The energy and emissions associated with raw material acquisition for these minerals is not included in the life cycle covered here. Unless the energy and emissions are significantly different than for pulpwood harvesting (which has a small effect compared to the manufacturing step), this is not likely to have a significant effect on the overall results.

5.1.1 RECYCLING

Recycling newsprint, fine paper, cardboard, and “other paper” provides emission benefits through the recovery of raw materials, in this case pulp, that reduces the need for virgin (or primary) production of those materials. The GHG emissions impacts of recycling newsprint, fine paper, cardboard, and “other paper” are presented in Exhibit 5-2. As can be seen below, forest carbon storage is the primary driver of overall GHG emission benefits.

Exhibit 5-2. Recycling Emissions for Newsprint, Fine Paper, Cardboard, and Other Paper (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Material Type	Process Energy	Transportation Energy	Process Non-Energy	Forest Carbon Sink	Net Emission Factor (=a + b + c + d)
Newsprint	(0.28)	(0.01)	0.00	(2.45)	(2.75)
Fine Paper	(0.36)	(0.00)	0.00	(2.84)	(3.20)
Cardboard	(0.20)	(0.01)	0.00	(3.04)	(3.26)
Other Paper	(0.24)	(0.01)	0.00	(3.02)	(3.27)

5.1.1.1 Raw Materials Acquisition

Virgin Product: Since the forestry operations for pulpwood harvesting do not vary by paper type, the same energy data applies to all four paper types included in this report. To develop estimates of GJ of energy per tonne of pulpwood, total fuel consumption by the forestry sector for harvesting, in megalitres by fuel, was obtained from Statistics Canada (2001). The energy content for each fuel, also provided by Statistics Canada, was then used to convert megalitres into GJ. It was estimated that 50 percent of the total energy consumption was used to harvest. According to Natural Resources Canada’s database (NRCAN 2004), the production of pulpwood in 2001 was approximately 9.6 million tonnes. Given the GJ of energy use for harvesting pulpwood and production, the energy intensity of acquisition of pulpwood for production of paper products was derived by dividing the GJ of energy consumption by tonnes of pulpwood production. These calculations are shown in Exhibit B-49.

Recycled Product: Energy associated with the “raw materials acquisition” of paper made from recycled product refers to fuel and electricity consumed at materials recovery facilities (“MRFs”), where the usable portion of secondary paper is isolated from other materials. To develop this estimate, a benchmark value of 0.6 kg eCO₂ per tonne of waste associated with energy use at waste management facilities was used (Torrie Smith Associates, 2003). In using this value, it was assumed that “waste management facilities” represent a reasonable surrogate for MRFs. After then assuming that the energy associated with these emissions is exclusively electricity, this estimate was converted to kWh of equivalent electricity, and subsequently into GJ of energy to estimate MRF GHG emissions which are presented in Exhibit B-50.

The effects of recycling on forest carbon storage comprise a significant component of the net GHG emission factor. The approach for analysing forest carbon effects is described in section 2.2.1.5.

5.1.1.2 Manufacturing and Fabrication

Energy data for manufacturing/fabrication are shown in Exhibit B-39 through Exhibit B-46 for virgin and recycled inputs, respectively. As noted in the original (2001) version of this report, energy estimates for manufacturing the four broad categories of paper products in this analysis were based on estimates of energy requirements and fuel mix for various manufacturing processes and products. In the case of virgin material production, fine papers are assumed to be made from bleached kraft, newsprint from mechanical pulp, and cardboard and mixed paper from an “average” chemical pulp, based on data provided by the Pulp and Paper Research Institute of Canada (1993). Energy data for paper production from recycled fibre was obtained from MK Jaccard and Associates and Willis Energy Services Ltd. (1996). Since publication of our original report, although additional data on paper manufacturing from a number of sources was researched, the most complete information was contained in the 1993 and 1996 data sets. It was assumed that these data sets include the energy associated with fabrication of paper sheets into final paper product (e.g., newsprint).

5.1.1.3 Transportation

No Canadian data were readily available on transportation associated with paper production. Consequently the transportation estimates were based on the following, as shown in Exhibit B-19 and Exhibit B-20.

Raw Materials Acquisition (Virgin Production): Estimates of transportation associated with the harvesting of paper (0.6 GJ/tonne) were based on data for steel, as provided in the Athena Institute report (Athena Institute 1998). This estimate can undoubtedly be improved with better data, but due to the relatively small contribution of this component to the total life-cycle energy for paper products, steel was assumed to be a reasonable surrogate.

Manufacturing and Fabrication (Virgin and Recycled Production): Due to the lack of readily-available transportation energy estimates for manufacturing and fabrication of paper, a rough estimate (0.07 GJ/tonne) was developed through the following steps: 1) assumed a typical distance of 100 km of truck transport per tonne during manufacturing and fabrication; 2) converted this estimate to litres of diesel fuel using an assumed fuel economy of 2.3 km per litre; 3) converted this fuel estimate to energy using data on the heat content of diesel; and 4) converted the resulting fuel intensity value to GHG emissions based on the carbon content of diesel fuel. This calculation is shown in Exhibit B-21.

Transport to End Use (Virgin and Recycled Production): The estimate for transporting paper from the manufacturing plant to the market (0.3 GJ/tonne) was based on an estimated transportation distance of 426 km of truck transport to ship glass to the market (i.e., glass was used as a surrogate for paper). The value for glass was provided by Jamie Meil of the Athena Institute. This estimate was converted to the equivalent amount of GJ of diesel fuel using the

same method as described above for “manufacturing and fabrication.” This calculation is shown in Exhibit B-22.

5.1.1.4 Open Loop Recycling

Several forest product materials are typically recycled in an open loop fashion. Open loop recycling can be described as a process where the primary raw material type is recovered and used to produce a different secondary material type. For example, when fine paper is recycled in Canada, a portion of the recovered material is typically used to produce writing or tissue paper, and a portion is used to produce cardboard (RIS 2004). In other words, recycled fine, or office paper in Canada is used to produce other types of forest products. The open loop recycling concept applies to each of the four forest product materials evaluated. Addressing the forest product open loop life-cycle phenomenon results in a more accurate depiction of the energy and GHG emission profile than simply assuming a closed loop (e.g., all recovered newsprint is used to produce more newsprint) recycling process. Exhibit 5-3 lists each primary forest product type along with its open loop recovery (or cross product flow) weighting for their respective secondary products. The secondary materials are typically produced when the primary material is recycled.

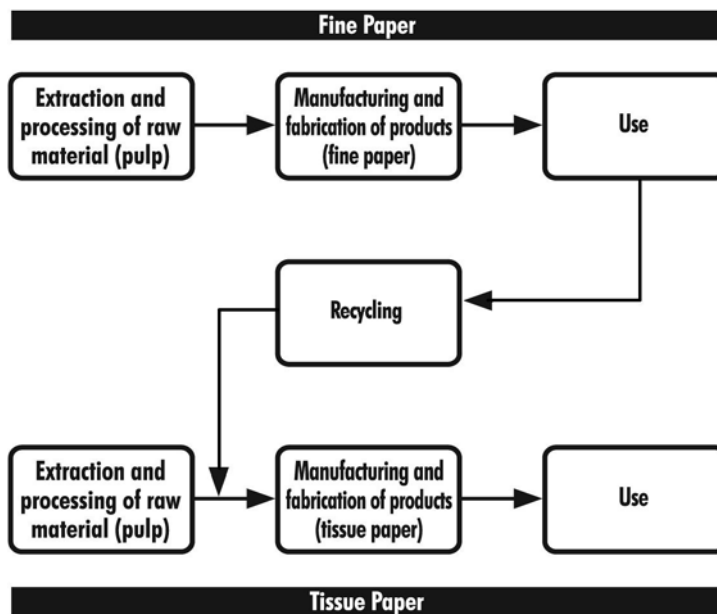
Exhibit 5-3. Forest Product Secondary Product Distribution

Forest Product	Newsprint	Fine Paper	Writing/Tissue Paper	Cardboard
Newsprint	90%	10%		
Fine Paper			80%	20%
Cardboard		20%		80%
Other Paper		25%		75%

(RIS 2004)

The open loop recycling process for newsprint, fine paper, cardboard, and other paper is implemented in our analysis by creating a weighted average by factoring the above percentages by the estimated energy and GHG emission differential between virgin and recycled manufacturing for each secondary material type. Creating the open loop for fine paper required that energy data associated with the production of writing/tissue paper be included in the analysis (FAL 2000). This data is specific to tissue paper production in the United States, though it is believed that the difference between production processes when compared to Canada would not be significant (particularly since many of the companies are active in both countries). The energy data associated with the production of tissue paper is in Exhibit B-47 and Exhibit B-48. Figure 4 below provides an illustration of open loop recycling for fine paper.

Figure 4. Fine Paper Open Loop Recycling



5.1.2 ANAEROBIC DIGESTION

This section describes the approach to developing the CH₄ and CO₂ emissions factors and carbon storage rates for anaerobic digestion (AD) facilities, which are designed to promote rapid anaerobic decomposition of solid waste; the resulting CH₄ (and other gases) is used as an energy source, from which electricity (and sometimes steam) is recovered. AD facilities can receive either source separated organics or mixed solid waste. In the case of the former, some paper may be targeted for inclusion depending on local circumstances (especially distance to fibre markets). In the latter case, various paper based items are present in the refuse stream, having evaded capture via local recycling programs, and as a result the AD facility ends up digesting fibre. The emission factors presented here apply to either situation, and assume that the extent of decomposition for a given material is not affected by the composition of the broader waste mass that is co-managed in the AD facility.

Relatively little information is available on the GHG emissions and sinks from this waste management process – few AD facilities are in operation, and AD is not analysed in the U.S. study that provided a framework and default data for other management processes addressed in this report.

There are three categories of potential GHG emissions or sinks/offsets from forest product AD facilities: CH₄ emissions, electricity offsets, and the soil carbon sink.¹⁹ Although monitoring

¹⁹ The AD process also generates CO₂ emissions from decomposition of organic inputs. As explained earlier, CO₂ from biogenic, sustainable harvested sources is not counted in emission inventories, so it is not addressed here.

data on CH₄ emissions was not located, based on the fact that AD facilities are designed and operated to capture CH₄ it is reasonable to assume that these fugitive emissions are negligible. Thus, our efforts focused on electricity offsets and soil carbon storage, which are described below.

Electricity Offsets: As discussed earlier, when waste management facilities generate electricity, they can offset the use of fossil fuel at other electric generating units. For purposes of evaluating the effect of energy efficiency, renewables, or other offsets, it is Canada's policy to assume that the marginal fuel that is offset by electricity utility operators is natural gas. The key steps in estimating the magnitude of electricity offsets were to (1) estimate the yield of CH₄ in anaerobic digestion facilities, on a material-specific basis, and (2) estimate the conversion efficiency (or heat rate) of CH₄ to electricity.

Information on material-specific AD yields of CH₄ was not found. Therefore, material-specific data for the CH₄ and CO₂ yields from lab studies of anaerobic digestion of municipal solid waste (MSW) in landfills (Barlaz 1997) was apportioned based on the overall yield of CH₄ at AD facilities using MSW as the feed. An extensive review of literature on AD performance was conducted, from which a typical figure for CH₄ yield (0.22 m³/kg volatile solid) was determined for MSW in AD reactors.

A composition profile (based on waste audit data) for residential and IC&I waste for a typical Ontario municipality (Guelph, Ontario) was assumed. Estimates of carbon content, moisture content, and volatile solids (VS) were determined using data from Barlaz (1998) and other sources.

The material-specific yield data (m³ CH₄/kg VS) from lab tests of landfill conditions were applied to the waste composition profile and calibrated to the typical overall yield for waste AD reactors according to the proportions and potential CH₄ yield of each material. Among the forest products, the estimated material-specific yields ranged from 0.07 tonnes CH₄ per wet tonne for newspaper to 0.21 tonnes CH₄ per wet tonne for fine paper.

The biogas from anaerobic digesters is upgraded for energy use by removing moisture, CO₂, and other by-products. This gas can be used as a substitute for natural gas, either in boilers producing hot water and steam for industrial processes or to generate electricity. Energy is needed for the process (heating, mixing, drying, etc.) and is usually supplied from the biogas product.

Based on the limited information available, it was assumed that the process efficiency (ratio of the energy content of CH₄ to the energy delivered as electricity) for AD is the same as that for landfill gas to energy facilities. Based on an assumption that electricity is generated through use of internal combustion engines, the process efficiency is 23.6 percent.

Soil Carbon Storage: In the same way that residual carbon from the composting process can enhance carbon storage when applied to soil, the undegraded carbon exiting the AD process has the potential to provide some benefit in the form of carbon storage. After digesting waste anaerobically, AD facilities typically use aerobic composting to further stabilize the organic

materials. It was assumed that the resulting compost would then be applied to soils as a soil amendment.

Information on the composition of finished compost from this process was not found, so the carbon content of the compost material was estimated using an analogy with yard trimmings compost (from centralized, aerobic composting). Key assumptions are:

- Residual carbon for each material in the waste feed can be calculated by deducting biogas formation from initial carbon concentration. Biogas is assumed to comprise 55 percent CH₄ and 45 percent CO₂.
- For yard trimmings, the residual carbon content remaining after the AD/aerobic sequence is the same as the residual carbon after centralized composting. Based on this assumption, one can compare the proportion of total degradation that occurs during the aerobic phase to the proportion occurring in the anaerobic phase of the process (the calculated ratio is 1.25:1, i.e., more than half of the decomposition occurs aerobically).
- The same ratio of 1.25 aerobic to 1 anaerobic applies to the other organic materials, subject to a mass balance constraint on available carbon. This level of aerobic degradation would be sufficient to decompose all of the available carbon for all of the remaining organic materials except for newsprint.
- For the two materials (newsprint and yard trimmings²⁰) assumed to have residual carbon, it was assumed that the soil carbon benefit would be equivalent to the soil carbon restoration component of the benefit from composted yard trimmings.²¹

Because neither newsprint nor yard trimmings generate much CH₄, their soil carbon benefits exceed the CO₂ emissions avoided through electricity offsets from anaerobic digestion. The net GHG emission benefits for anaerobic digestion are presented in Exhibit 5-4.

²⁰ Yard trimmings are addressed in the next chapter.

²¹ This does not include another component of the benefits of centralized yard trimmings composting – formation of humic materials through the aerobic composting process. If this component were included, the soil carbon benefit for AD of yard trimmings would be exactly the same as the soil carbon benefit for centralized yard trimmings composting.

Exhibit 5-4 Anaerobic Digestion Emissions for Newsprint, Fine Paper, Cardboard, and Other Paper (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Material Type	Transportation to Digestion Facility Energy	Anaerobic Digestion CH ₄	Avoided Utility Emissions	Soil Carbon Sink	Net Emissions (Post-Consumer) (=a + b + c + d)
Newsprint	0.01	0.00	(0.12)	(0.39)	(0.49)
Fine Paper	0.01	0.00	(0.35)	0.00	(0.34)
Cardboard	0.01	0.00	(0.24)	(0.08)	(0.32)
Other Paper	0.01	0.00	(0.24)	(0.01)	(0.23)

5.1.3 COMBUSTION

The potential GHG emissions and sinks to consider for the combustion of forest products include CO₂ and N₂O from the combustion process and electricity offsets from recovery of energy. Emission factors for CO₂ emissions from incineration were not developed because forest products are derived from biogenic, sustainably harvested sources. Our work in developing estimates for N₂O emissions and electricity offsets is described below.

Nitrous Oxide Emissions: For this category, the same assumptions as in our work for U.S. EPA were used (EPA 2002). Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that waste combustion results in measurable emissions of N₂O, a GHG with a high global warming potential (IPCC 1996). The IPCC compiled reported ranges of N₂O emissions, per tonne of waste combusted, from six classifications of MSW combustors. The midpoints of each range were averaged; the resulting estimate is 0.04 tonne eCO₂ of N₂O emissions per tonne of mixed MSW combusted. Because the IPCC did not report N₂O values for combustion of individual components of residential and IC&I waste, this was used as a surrogate for all components of MSW that contain nitrogen (i.e., forest products and organics).

Electricity Offset: Unpublished waste throughput and energy production data compiled by Environment Canada were reviewed to evaluate the energy from waste (EFW) incineration facilities in Canada. Depending on the facility, hot water, steam and electricity are produced. For purposes of this analysis, however, only the GHG offsets associated with electricity generation were estimated. This implicitly assumes that the relationships between fossil fuel and EFW system efficiencies and fuel types are the same for water and steam production as they are for electricity generation. U.S. EPA data (EPA 2002) was used for the energy content of each waste material category. A composition profile (based on waste audit data) for a typical Ontario municipality (Guelph, Ontario) was assumed to determine an average energy content of residential and industrial, commercial, and institutional (IC&I) waste feed. This is the same composition information as that used for analysis of emission factors for anaerobic digestion. While actual waste generation profiles across Canada are likely to vary significantly, the use of Guelph, Ontario as a surrogate is a reasonable assumption.

The average net rate of electricity generated and exported from the six Canadian facilities compared was determined to be 14.8% of the energy content of the residential and IC&I waste feed. This is net of energy used in the process and includes the conversion efficiency to electricity, as well as transmission and distribution losses (assumed to be 10 percent). As shown in Exhibit 5-5 the GHG emission impact of combusting newspaper, fine paper, cardboard, and other paper is 0.05, 0.04, 0.04, and 0.04 tonnes eCO₂/ton respectively.

Exhibit 5-5 Combustion Emissions for Newsprint, Fine Paper, Cardboard, and Other Paper (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Material Type	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Net Combustion Emissions (=a + b +c)
Newsprint	0.04	0.01	(0.10)	(0.05)
Fine paper	0.04	0.01	(0.09)	(0.04)
Cardboard	0.04	0.01	(0.09)	(0.04)
Other Paper	0.04	0.01	(0.09)	(0.04)

5.1.4 LANDFILLING

There are three categories of potential GHG emissions or sinks/offsets from the landfilling of forest products in municipal solid waste: CH₄ emissions, landfill carbon sink, and electricity offsets.²² CH₄ emissions from landfilling were estimated using the values presented in U.S. EPA (EPA 2002).

Methane Generation: CH₄ yields were developed using experimental data collected by Dr. Morton Barlaz (Barlaz 1997). Dr. Barlaz collected data on the amount of CH₄ generated by organic materials, when digested by bacteria in anaerobic conditions simulating those in a landfill. Portions of each material were weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under warm, moist conditions designed to accelerate decomposition. The reactors were seeded with a small amount of well-decomposed refuse containing an active population of CH₄ producing microorganisms (the “seed”), to ensure that CH₄ generation was not limited due to an insufficient population of microorganisms. To promote degradation, water was cycled through each reactor. Nitrogen and phosphorus were then added so that CH₄ generation would not be limited by a lack of these nutrients.

²² Landfills also generate CO₂ emissions from decomposition of organic inputs. As explained earlier, CO₂ from biogenic, sustainable, harvested sources is not counted in emission inventories, so it is not addressed here.

Dr. Barlaz measured the amount of CH₄ generated in each reactor, and the amount of undecomposed carbon remaining in each reactor at the end of the experiment. Each material was tested in four reactors, and the results from each were averaged (Barlaz 1997). At the start of the experiment, Dr. Barlaz dried a sample of each material, and analyzed the amount of cellulose, hemicellulose, and lignin (and, for food discards, protein) in each material. Cellulose, hemicellulose, and protein partly decompose in a landfill, resulting in CH₄ generation; lignin is relatively stable and non-decomposable under anaerobic conditions.

Dr. Barlaz measured the amount of CH₄ generated during the experimental period, and subtracted the amount of CH₄ attributable to the seed in order to obtain the amount of CH₄ generated by the material being tested. At the end of the experiment, he opened the reactors, drained the leachate, dried and weighed the contents, and analyzed the percentage composition of cellulose, hemicellulose, and lignin (and, for food discards, protein) in the remaining contents. He then measured the percentage of total volatile solids in the remaining contents. This amount included the cellulose, hemicellulose, lignin, and protein, and any other carbon-containing components such as waxes and tannins.

Dr. Barlaz’s experiment did not specifically test “other paper” as defined for recycling purposes, but it did evaluate four specific grades of paper—newsprint, corrugated boxes, office paper, and coated (e.g., waxed) paper. Other paper recyclers can attest to the wide variety of paper types (and other contaminants) that compose the “other paper” category, as a simplifying assumption it was assumed that this category has only four components. Specifically, emissions were calculated using the values obtained from Dr. Barlaz’s experiment for newsprint, fine paper, cardboard, and coated paper, according to the assume composition of “other paper” presented in Exhibit 5-6, which is based on proportions used in the US study (EPA 2002).

Exhibit 5-6. Definition of Other Paper

Paper Types	Fraction of Each Paper Type in “Other Paper”
Newsprint	5
Fine Paper	60
Cardboard	30
Coated	5

Dr. Barlaz then checked his experimental results by estimating the amount of CH₄ that would have been produced if all of the cellulose, hemicellulose, and protein from the waste material that was decomposed during the experiment had been converted to equal parts of CH₄ and CO₂ (CH₄ producing microorganisms generate equal amounts, by volume, of CH₄ and CO₂ gas) (Barlaz 1997). Dr. Barlaz referred to this amount as the material’s “CH₄ potential.” He then calculated the percentage of the CH₄ potential for each material accounted for by the sum of (1) the measured CH₄ generation, and (2) the amount of CH₄ that could be formed from the carbon in the leachate that was removed from the reactor, and from the carbon in the refuse that

remained in the reactor at the end of the experiment.²³ CH₄ potential not accounted for could be due to either (1) leaks of CH₄, (2) measurement error, or (3) carbon in the cell mass of microorganisms (which was not measured).

CH₄ recovery was below 85 percent of the “CH₄ potential” for five materials: office paper, coated paper, food discards, leaves, and branches. In EPA’s analysis of the data set, they chose to assume that some of this “missing carbon” was converted to microorganism cell mass, and the remainder was degraded. Dr. Barlaz postulated a higher CH₄ yield based on assumptions that (1) five percent of the carbon in cellulose and hemicellulose (and protein in the case of food discards) that was degraded was converted into the cell mass of the microbial population, and (2) 90 percent of the carbon-containing compounds that were degraded but not converted to cell mass were converted to equal parts of CH₄ and CO₂. The “corrected yields,” based on these assumptions, are reflected in the EPA report and are also used in the current analysis.

Methane Emitted: This analysis accounted for (1) the conversion in the landfill of some portion of landfill CH₄ to CO₂, and (2) the capture of CH₄, either for flaring or for combustion with energy recovery (in either case, the captured CH₄ is converted to CO₂).²⁴

To estimate waste CH₄ emissions from landfills with and without landfill gas (LFG) recovery, the percentage of landfill CH₄ that is oxidized near the surface of the landfill was estimated. It was estimated that 10 percent of the landfill CH₄ that is generated is either chemically oxidized or converted by bacteria to CO₂ (Liptay 1998, Czepiel 1996) and that the remaining 90 percent is available for atmospheric CH₄ emissions (EPA 1993).

Next, CH₄ emissions for three categories of landfills were estimated: (1) landfills without LFG recovery, (2) landfills with LFG recovery that flare LFG, and (3) landfills with LFG recovery that generate electricity from the LFG. To estimate waste CH₄ emissions from landfills with LFG recovery, it was assumed that these landfills have an average LFG recovery efficiency of 75 percent (EPA 2002).

CH₄ emissions for the “national average landfill” were also calculated. Emissions from the national average landfill reflect CH₄ emissions from all three types of landfills, weighted by the fraction of landfills in Canada that fall into each category. Based on an analysis of data on landfill gas collection systems at operating Canadian landfills, it was assumed that 63 percent of the landfills in Canada do not recover LFG. Of the remaining 37 percent, it was assumed that 39 percent recover and flare LFG and 61 percent recover energy from LFG (all recovery is assumed to result in electricity generation).

Landfill Carbon Sink: Carbon storage estimates were also taken from experimental data collected by Dr. Barlaz and presented in U.S. EPA’s report on GHG emissions from solid waste

²³ Note that any carbon that was converted to cell mass in microorganisms was not considered in this calculation.

²⁴ The CO₂ that is emitted is not counted as a GHG because it is biogenic in origin.

management (EPA 2002). Carbon storage was estimated by calculating the amount of carbon remaining in each reactor at the end of the experiment, and then subtracting the amount of carbon remaining that was attributable to the seed. The difference between the two values is the amount of carbon from the waste material that remained in the reactor, undecomposed, at the end of the experiment. Since the conditions in the reactor simulated landfill conditions, this is approximately the amount of carbon that would be stored if the material were landfilled (Barlaz 1998). Note that the experimental conditions (abundant moisture, nutrients, and anaerobes) probably represent a more favourable situation for decomposition (and less favourable for carbon storage) than conditions in most landfills, and thus the results may be biased toward overstating GHG emissions from landfills.

Electricity Offset: As mentioned above, our analysis assumes that 37 percent of landfills in Canada recover LFG. Of those, 29 percent are assumed to recover and then combust LFG for electricity generation. These landfills offset CO₂ emissions from avoided electricity generation at utilities.

Avoided CO₂ emissions per tonne of CH₄ recovered and combusted were estimated assuming a landfill gas conversion efficiency of 23.6 percent (energy content of CH₄ converted to delivered electricity, after accounting for transmission and distribution losses of 10 percent) and 108 tonnes eCO₂ avoided per TJ of offset electricity. As seen in Exhibit 5-7, landfilling newsprint has a negative GHG emissions profile, while fine paper, cardboard, and other paper have net positive GHG emissions due to higher levels of methane generation. The emission factors are sensitive to whether or not the landfill has a gas collection system (and the assumed capture efficiency of that system).

Exhibit 5-7 Landfilling Emissions for Newsprint, Fine Paper, Cardboard, and Other Paper (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Material Type	Waste Collection and Transportation	Net Landfill CH ₄	Avoided Utility Emissions	Landfill Carbon Sink	Net Emissions (Post-Consumer) (=a + b + c + d)
Newsprint	0.01	0.22	(0.00)	(1.45)	(1.22)
Fine Paper	0.01	1.34	(0.01)	(0.17)	1.18
Cardboard	0.01	1.18	(0.01)	(0.91)	0.29
Other Paper	0.01	1.21	(0.01)	(0.51)	0.71

5.1.5 LIMITATIONS

The emission factors presented in this section represent average conditions that may not accurately characterize national or site-specific conditions. For example, the raw material acquisition and manufacturing energy data is based on Canadian paper industry data as a whole (PPRIC 1993; MK Jaccard and Associates and Willis Energy Services Ltd. 1996). There is likely to be some variation between individual paper and cardboard production facilities with

respect to energy consumption efficiency and fuel type. Site-specific variability is also a concern with each of the end-of-life management options (e.g., combustion transport distances). In addition, these values do not address international cross-border flows. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with paper recycling, landfilling, and combustion activities from a national average perspective.

The emission factors for paper are also quite sensitive to values for forest carbon storage (for recycling), methane yield (for landfills and AD), and landfill carbon storage. There are still many technical and policy issues to be worked out with respect to accounting for forest carbon storage in GHG inventories, so the values used here (which drive the recycling emission factors) are subject to considerable uncertainty. Similarly, the methane yields and landfill carbon storage estimates are based on a limited experimental data set, and the experiment was designed to encourage anaerobic decomposition, so the results are uncertain and may contain a bias to overstate CH₄ emissions and understate storage. Finally, although landfill carbon storage has been included in the national GHG inventories of the US and Australia, there is certainly not a consensus on either the methodology or underlying conceptual basis for including this factor in GHG accounting.

6 Organics

This section covers two common organic wastes, food scraps and yard trimmings. Because they are not manufactured, these materials are treated somewhat differently than most of the others in this analysis – there are no emissions associated with energy use in the raw material acquisition and manufacturing steps. However, like forest products, landfilling results in some CH₄ emissions as well as long term carbon storage. Moreover, the analogue for recycling – composting – has an effect on carbon storage in soils, and so that management option is evaluated for organics (but not for any other materials).

6.1 Food Scraps and Yard Trimmings

The net GHG emission factors for the various waste management options for yard trimmings and food scraps are shown in Exhibit 6-1, and their derivation is discussed below.

Exhibit 6-1. GHG Emissions from MSW Management Options for Yard Trimmings and Food Scraps (tonnes eCO₂/tonne)

	Net Composting Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE) - National Average
Food Scraps	(0.24)	(0.10)	0.02	0.80
Yard Trimmings	(0.24)	(0.15)	0.01	(0.33)

6.1.1 COMPOSTING

The composting of organics may result in (1) CH₄ emissions from anaerobic decomposition, (2) long-term carbon storage in the form of “un-decomposed” carbon compounds, and (3) non-biogenic CO₂ emissions from collection and transportation of the organic materials to the central composting site, and from mechanical turning of the compost pile.²⁵ The composting of organics also results in biogenic CO₂ emissions associated with decomposition, both during the composting process and after the compost is added to the soil. However, because this CO₂ is biogenic in origin, it is not included in international accounting guidelines and is not included in our accounting of emissions and sinks.

²⁵ CO₂ emissions from delivery of compost to its final destination were not counted, because compost is a marketable product, and CO₂ emissions from transportation of other marketable, finished goods to consumers have not been counted in other parts of this analysis.

Our analysis suggests that composting of organics, when managed properly, does not generate CH₄ emissions, but results in some carbon storage (associated with application of compost to soils), as well as minimal CO₂ emissions from mechanical turning of the compost piles. In order to maintain consistency with the methodology used for forest carbon sinks, point estimates were selected from the range of emission factors – covering various compost application rates and time periods – developed in an earlier analysis conducted by ICF for U.S. EPA. The point estimate was chosen based on a “typical” compost application rate of 20 short tons of compost per acre, averaged over three soil-crop scenarios. In terms of timing, the carbon storage values for the year 2010 were selected to be consistent with forest carbon storage estimates. The composting GHG emissions associated with food scraps and yard trimmings are presented in Exhibit 6-2.

Exhibit 6-2 Centralized Composting Emissions for Food Scraps and Yard Trimmings (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Material Type	Compost Equipment CO ₂	Compost CH ₄	Soil Carbon Sink	Net Emissions (Post-Consumer = a + b + c)
Food Scraps	0.02	0.00	(0.27)	(0.24)
Yard Trimmings	0.02	0.00	(0.27)	(0.24)

Carbon Dioxide from Turning of Compost: To estimate the indirect CO₂ emissions associated with turning the compost piles the analysis began with estimates developed by Franklin Associates for the amount of diesel fuel required, for one tonne of organics,²⁶ to turn the compost piles (211 MJ) (FAL 1994). Using the carbon coefficient for diesel, this estimate was converted to 0.018 tonnes eCO₂/tonne of forest products composted at a central composting facility.

Soil Carbon Sink: The U.S. EPA analysis of carbon storage investigated the extent to which composting restores soil carbon in degraded soils and increases formation of stable carbon compounds (e.g., humic acids, aggregates). The analyses of soil carbon restoration, nitrogen fertilization, and incremental humus formation apply relatively simple models of very complex processes. These processes probably are controlled by many biological, physicochemical, and compost management factors, such as type and rate of application (i.e., silviculture, horticulture, agriculture, and landscaping); regional and local climatic factors; soil type; and, to a lesser extent, compost feedstock (e.g., grass, leaves, branches, yard trimmings, food discards). In addition, the results are time-dependent, so the year in which benefits are assessed has an effect on the magnitude of carbon storage. Understanding these limitations, the analysis provides a set

²⁶ Measured on a wet weight basis, as MSW is typically measured.

of first approximations that quantify the extent of soil carbon storage associated with composting, as compared to landfilling and combustion.

Soil carbon storage is a function of carbon restoration and incremental humus formation, as discussed below.

Soil Carbon Restoration: The CENTURY model was used (Metherell et al. 1993) to quantify the impact of composting on soil carbon restoration. The key inputs to the analysis are listed below:

- Compost application rates of 1.3, 3.2, 6.5, 10, 15, 20, and 40 wet short tons of compost/acre/year for 10 years from 1996-2005 and 1.3 and 3.2 wet short tons of compost/acre applied every 5 years (e.g., 1996, 2001, and 2006).
- Compost parameters included 33% lignin content, 17:1 carbon to nitrogen ratio, 60:1 carbon to phosphorus ratio, and 75:1 carbon to sulphur ratio.
- Two site files: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil.
- Two harvest regimes: one where the corn was harvested for silage (95% aboveground biomass removal) and another where the corn was harvested for grain and remains were left on the field.

For each scenario, the model estimated carbon storage in units of grams of carbon per square meter for all soil carbon pools. Model outputs were analysed to isolate the effects of compost carbon addition from total carbon added to the soil (including crop residues). Results were then converted to units of carbon per unit of compost by dividing the increase in carbon storage by the mass of organics required to produce the compost.

Incremental Humus Formation: A bounding analysis was used to estimate the effect of incremental humus formation. The bounding analysis was predicated on two key factors: (1) the fraction of carbon in compost that is considered “passive” (i.e., very stable) and (2) the rate at which passive carbon is degraded to CO₂.

Estimates for the first factor were based on experimental data compiled by Dr. Michael Cole of the University of Illinois, as reported by USEPA (2002). Dr. Cole found literature values indicating that between 4 and 20 percent of the carbon in finished compost degrade quickly.²⁷ Dr. Cole averaged the values he found in the literature and estimated that 10 percent of the carbon in compost can be considered “fast” (i.e., readily degradable). The remaining 90 percent of carbon in compost can be classified as either slow or passive.

²⁷ Very little information is available on the characteristics of compost derived from yard trimmings or food scraps. However, Dr. Cole found that the composition of composts derived from other materials was broadly consistent, suggesting that his estimates may be reasonably applied to yard trimmings or food scrap compost.

Experimental data was not located that delineates the fractions of slow and passive carbon in compost; therefore, upper and lower bound estimates based on Dr. Cole’s professional judgement were developed. He suggested values of 30 percent slow and 60 percent passive, and 45 percent slow and 45 percent passive for the upper and lower bounds on passive content, respectively.²⁸ For the second factor, a mean residence time for passive carbon of 400 years based on the range of values specified in the literature was chosen (Metherell et al. 1993 and Brady et al. 1999). Combining the two bounds for incremental humus formation (60 percent passive and 45 percent passive), the incremental carbon storage implied by each scenario was estimated.

Net GHG Emissions from Composting: Although the two approaches used to quantify soil carbon storage capture the range of potential benefits, they create the possibility of double counting. In an effort to eliminate double counting, the way that CENTURY partitions compost carbon once it is applied to the soil was evaluated. Based on our analysis, it appears that CENTURY is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent), the CENTURY results were scaled by 48 percent to reflect the proportion of carbon that can be classified as fast or slow. The derivation of net carbon flux associated with composting is detailed in Exhibit 6-3.

Exhibit 6-3 Net GHG Emissions for Composting Calculations

Unweighted Carbon Content	Proportion of C that is not passive	Weighted estimate	Increased Humus Formation	Net Carbon Flux MTCE/tonne	Net Carbon Flux Tonne eCO ₂ /tonne
(0.04)	48%	(0.02)	(0.05)	(0.07)	(0.27)

6.1.2 ANAEROBIC DIGESTION

The analysis for the anaerobic digestion of organics used the same parameters as the forest products anaerobic digestion analysis that is discussed above. In determining the electricity offsets, the estimated material-specific yields were 0.14 tonnes CH₄ per wet tonne for food waste and 0.08 tonnes CH₄ per wet tonne for yard waste. The soil carbon storage calculations were identical to the calculations performed for organics. The GHG emission impacts resulting from the anaerobic digestion of food scraps and yard trimmings are presented in Exhibit 6-4.

²⁸ Only the passive pool was focused on because (1) the Century model does not allow for direct input of organic carbon into the passive pool and (2) the model runs resulted in very little indirect (i.e., via other pools) formation of passive carbon. Although the first factor is also true for the slow pool, the second is not. Had slow carbon been analyzed in the same way as passive carbon, there would be potential for double-counting.

Exhibit 6-4 Anaerobic Digestion Emissions for Food Scraps and Yard Trimmings (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Material Type	Transportation to Digestion Facility Energy	Anaerobic Digestion CH ₄	Avoided Utility Emissions	Soil Carbon Sink	Net Emissions (Post-Consumer =a + b + c + d)
Food Scraps	0.01	0.00	(0.11)	0.00	(0.10)
Yard Trimmings	0.01	0.00	0.00	(0.16)	(0.15)

6.1.3 COMBUSTION

As with the combustion of forest products that is discussed previously, the potential GHG emissions and sinks from the combustion of organics are CO₂ and N₂O from the combustion process and electricity offsets from recovery of energy. Our analysis of these emissions and sinks is identical to the forest products analysis. Emission factors for CO₂ emissions from incineration were not developed because organics are derived from biogenic, sustainably harvested sources. As for N₂O, an emission factor of 0.04 tonne eCO₂ of N₂O emissions per tonne of mixed MSW combusted was estimated based on an average of the midpoints of IPCC's reported ranges of N₂O emissions, per tonne of waste combusted, from six classifications of MSW combustors. The average net rate of electricity generated and exported from the six Canadian facilities compared was determined to be 14.8% of the energy content of the MSW feed from a typical Ontario municipality (Guelph, Ontario). This is net of energy used in the process and includes the conversion efficiency to electricity, as well as transmission and distribution losses (assumed to be 10 percent). As shown in Exhibit 6-5, the GHG emissions of combusting food scraps and yard trimmings are 0.02, and 0.01 tonnes eCO₂/ton respectively.

Exhibit 6-5 Combustion Emissions for Food Scraps and Yard Trimmings (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Material Type	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b + c + d)
Food Scraps	0.04	0.01	(0.03)	0.00	0.02
Yard Trimmings	0.04	0.01	(0.04)	0.00	0.01

6.1.4 LANDFILLING

There are three categories of potential GHG emissions or sinks/offsets from the landfilling of organics in municipal solid waste: CH₄ emissions, landfill carbon storage, and electricity

offsets.²⁹ The methodology used to estimate these GHG emissions and sinks/offsets is identical to the methodology used to analyze the previously discussed landfilling of forest products.

The emission factors for yard trimmings are derived from data reported by Barlaz (1997) for grass, leaves, and branches. The assumed composition is based on an estimate of 39 percent grass, 27 percent leaves, 18 percent brush, and 16 percent inert material developed by Robert Sinclair of NRCan based on three studies of the composition of yard trimmings (IES 1999, CH2MHill 1999, RIS 2005).

As seen in Exhibit 6-6, landfilling food scraps generates net GHG emissions of 0.80 tonnes eCO₂/tonne while landfilling yard trimmings generates negative GHG emissions of 0.33 tonnes eCO₂/tonne.

Exhibit 6-6 Landfill Emissions for Food Scraps and Yard Trimmings (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Material Type	Transportation	Net Landfill CH ₄	Avoided Utility Emissions	Landfill Carbon Sink	Net Emissions (Post-Consumer) (=a + b + c + d)
Food Scraps	0.01	0.88	(0.01)	(0.09)	0.80
Yard Trimmings	0.01	0.42	(0.00)	(0.76)	(0.33)

6.1.5 LIMITATIONS

The emission factors for organics, like those of paper, are quite sensitive to values for methane yield (for landfills and AD) and landfill carbon storage. The methane yields and landfill carbon storage estimates are based on a limited experimental data set, and the experiment was designed to encourage anaerobic decomposition, so the results are uncertain and may contain a bias to overstate CH₄ emissions and understate storage. Finally, although landfill carbon storage has been included in the national GHG inventories of the US and Australia, there is certainly not a consensus on either the methodology or underlying conceptual basis for including this factor in GHG accounting.

²⁹ Landfills also generate CO₂ emissions from decomposition of organic inputs. As explained earlier, CO₂ from biogenic, sustainably harvested sources is not counted in emission inventories, so it is not addressed here.

7 Electronics and White Goods

This chapter presents the life-cycle approach used to estimate energy and emission factors for waste management approaches for typical types of electronics and white goods. These types of consumer goods are similar in that, from a waste management perspective, they can be viewed as composites of several basic materials. For purposes of this report, the GHG implications of electronics and white goods are characterized based on the properties of the principal component materials – plastic, aluminum, steel, copper, lead, and glass.

Electronics and white goods are composed of raw materials that are inert in the landfill environment, i.e., none of these materials contributes to downstream emissions associated with the decomposition of organic material. As with all other materials, there are only CO₂ emissions associated with the energy required for waste collection vehicles, transport to the landfill, and heavy equipment operation at the landfill, estimated to be 0.15 GJ/tonne. These goods are also non-reactive in an anaerobic digester, and the energy associated with this end-of-life option for these materials is 0.11 GJ/tonne for collection vehicles and transport to the digestion facility. Electronics and white goods are typically not composted due to their inertness and interference with the compost turning/aeration process.

The following sections provide details on the GHGs associated with recycling and combustion processes for electronics and white goods.

7.1 Electronics

This section presents the methodology used to estimate the recycling and combustion energy and GHG impacts of four electronic devices increasingly found in the municipal solid waste stream: personal computers, televisions, microwaves, and VCRs. As noted above, the life-cycle GHG impacts for electronics can be characterized by examining each component raw material. The primary material types in these devices are plastics, steel, cathode ray tube (CRT) glass, copper wire, and aluminum.

Due to the heterogeneity of materials between electronic devices, there may be significant variation in the composition of different personal computers, televisions, microwaves, or VCRs. Furthermore, some characterizations of PCs include monitors and peripheral equipment (e.g., keyboards, external cables, printers), while others exclude these components. However, extensive studies (RIS 2003a RIS 2003b) have recently been conducted by RIS International Ltd to estimate the material composition of these materials in the Canadian waste stream. The raw material compositions of the electronic devices examined in this analysis are provided in Exhibit 7-1 based on the RIS reports. Since electronics technology is continually progressing, (e.g., replacement of traditional PC monitors and televisions with “flat screen” monitors), the composition of electronics will likely change in the future.

Exhibit 7-1. Percent Material Composition of Four Electronic Devices

Material	PC & Monitor ¹	Televisions ²	Microwaves ³	VCRs ⁴
Copper	6.9%	2.1%	8.8%	11.0%
Lead	6.3%	4.7%	0.0%	0.0%
CRT (cathode ray tube) Glass	24.8%	54.8%	5.9%	0.0%
ABS (acrylonitrile-butadiene-styrene) resin	11.5%	15.2%	4.4%	11.5%
PPO/HIPS (polyphenylene oxide/ high impact polystyrene) resin	11.5%	15.2%	4.4%	11.5%
Aluminum	14.2%	0.2%	0.3%	0.0%
Steel Sheet	20.5%	7.3%	76.3%	45.0%
Zinc	2.2%	0.0%	0.0%	0.0%
Other	2.2%	0.0%	0.0%	0.0%

¹ Average sized CPU and monitor (RIS 2003b)

² 28-inch Bang & Olufsen (B&O) colour television (RIS 2003a)

³ 32 litre (1.1 cu. ft.) capacity (RIS 2003a)

⁴ Average sized video cassette recorder (University of Florida 2004)

When electronics are recycled, they are typically dismantled and/or shredded and divided into their component raw material types through a separation process. These recovered materials then enter their respective recycled material processing streams. For example, the recovered steel from a television is processed along with other types of secondary steel to go into the production of new steel products. Electronics are thus assumed to be recycled in an “open loop”– i.e., electronics are recycled into different second generation products rather than back into the original electronic device. Therefore, the life-cycle analysis of GHG emissions associated with electronics recycling must take into account the various second generation products, typically the fundamental raw material types from which they are built. The second generation products in this analysis include steel sheet, lead bullion, glass, copper, aluminum sheet, and asphalt. In some cases, the plastic materials are combusted in conjunction with the copper smelting process; however, in the absence of information on this process, the recovery of plastics is evaluated under the assumption that it is used in asphalt production (FAL 2002).

Exhibit 7-2 provides the net GHG emissions for each of the waste management options for each of the four types of electronics. As indicated in the table, recycling has the potential to achieve negative emissions for all four types. Combustion results in positive emissions for the three types with significant plastics content, but negative emissions for microwaves, which are primarily composed of ferrous materials (which are assumed to be separated magnetically in the ash stream and recycled).

Exhibit 7-2. GHG Emissions from MSW Management Options for Electronics (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions
Personal Computers	(1.60)	0.01	0.41	0.01
Televisions	(0.23)	0.01	0.75	0.01
Microwaves	(1.27)	0.01	(0.55)	0.01
VCRs	(0.95)	0.01	0.15	0.01

7.1.1 RECYCLING

Recycling electronics provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials (e.g., steel and plastic). The GHG emissions benefits of recycling electronics are presented in Exhibit 7-3.

Exhibit 7-3 Recycling Emissions for Personal Computers, Televisions, Microwaves, and VCRs (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Electronic Device	Process Energy	Transportation Energy	Process Non-Energy	Net Emission Factor (=a + b + c)
Personal Computers	(0.99)	(0.00)	(0.61)	(1.60)
Televisions	(0.34)	0.24	(0.12)	(0.23)
Microwaves	(1.23)	0.01	(0.05)	(1.27)
VCRs	(0.93)	(0.01)	(0.02)	(0.95)

7.1.1.1 Open Loop Recycling

When electronics are recycled, the raw material components (e.g., steel and aluminum) are recovered and distributed to their respective recovery pathways. Data associated with the recycling of electronics is largely based on the report, *Energy and Greenhouse Gas Factors for Personal Computers* by Franklin Associates (FAL 2002). That report, prepared for U.S. EPA in support of that agency's effort to develop GHG emission factors for materials in the U.S. waste stream, provides detailed life-cycle energy information related to the manufacture of raw material components of personal computers with raw materials acquisition, and manufacturing and fabrication data in an aggregated format. In the case of electronics, because they are composed of several raw material types, they may be recycled into asphalt, steel sheet, lead bullion, CRT glass, copper wire, and aluminum sheet. Details on the primary and secondary

recycling processes for steel sheet, aluminum sheet and copper wire are presented in Chapter 3 of this report.

The energy benefits of recycling electronics was calculated by comparing the difference in energy requirements associated with manufacturing a tonne of each of the secondary products from virgin versus recycled materials. The results for each of the secondary products were then weighted by the distribution shown in Exhibit 7-4 to obtain a composite emission factor for recycling a tonne of each electronic device. The energy required for shredding and processing the raw material stream obtained from recycling computers was also included. The shredding and processing energy for electronics recycling is estimated to be 680 MJ/tonne, all as electricity (Anonymous 2005).

Exhibit 7-4 Secondary Materials Produced from Recycled Electronics

Type of Product	Personal Computer	Televisions	Microwaves	VCRs
Asphalt (from plastics)	38%	8%	9%	23%
Steel Sheet	27%	11%	76%	45%
Lead Bullion	10%	0%	0%	0%
CRT Glass	2%	69%	6%	0%
Copper Wire	5%	4%	9%	11%
Aluminum Sheet	18%	0%	0%	0%

Sources: FAL (2002), RIS (2003a), RIS (2003b)

The transportation energy benefits associated with recycling electronics was calculated by comparing the difference in energy requirements associated with transporting a tonne of each of the secondary products from virgin versus recycled materials. The results for each of the secondary products were weighted by the distribution shown in Exhibit 7-4.

7.1.2 COMBUSTION

The impacts associated with combustion electronics were estimated by creating a composite of energy and GHG emission profiles associated with combustion of each of the raw materials that make up each electronic device. Key materials in this composite are steel (typically recovered magnetically in the combustion process), and plastics (CO₂ emissions and electricity offsets in the waste-to-energy conversion). The results for each of the secondary products were weighted by the distribution shown in Exhibit 7-4. The combustion energy and GHG emission factors for electronics are presented in Exhibit 7-5.

Exhibit 7-5 Combustion Emissions for Personal Computers, Televisions, Microwaves, and VCRs (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Electronic Device	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b + c + d)
Personal Computers	0.65	0.01	(0.04)	(0.21)	0.41
Televisions	0.86	0.01	(0.05)	(0.08)	0.75
Microwaves	0.25	0.01	(0.01)	(0.79)	(0.55)
VCRs	0.65	0.01	(0.04)	(0.47)	0.15

7.1.3 LIMITATIONS

The complexity of the electronics manufacturing and disposal/recycling system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent average conditions that may not accurately characterize national or site-specific conditions. This is especially true for electronics, which are composites of multiple materials (e.g., steel, aluminum, and plastic) and are recycled through an open-loop scenario. For example, the raw material acquisition and manufacturing energy data for the component materials is based on Canadian and U.S. information (depending on the material). There is likely to be some variation between individual production facilities with respect to energy consumption efficiency and fuel type. Site-specific variability is also a concern with each of the end-of-life management options (e.g., combustion transport distances). In addition, these values do not address international cross-border flows, which are quite significant for electronics recycling. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with electronics recycling, landfilling, and combustion activities from a national average perspective.

7.2 White Goods

This section presents the methodology used to estimate the life-cycle profile of white goods, which in this analysis includes the following appliances: refrigerators (top/bottom and side by side), freezers, dishwashers, ranges, clothes washers, and clothes dryers. Since each white good type can be thought of as a composite of various raw material types, the life-cycle impacts can be estimated using a weighted average of the life-cycle impacts of each individual component material. The primary material types in white goods are ferrous and nonferrous metal, plastic, and glass, with small amounts of rubber, paper, and other materials. Since the material composition of these appliances is relatively similar, a weighted average of the material composition in each type of appliance and created a generic “white good” material type was developed. This weighted average is based on the annual generated waste of these appliances obtained from the Canadian Appliance Manufacturers Association (CAMA 2000). The

composition of the average white good entering the Canadian waste stream is provided in Exhibit 7-6.

Exhibit 7-6 Raw Material Composition of Canadian White Goods

Material Type	Percent Composition
Glass	4.9%
Plastic	17.5%
Ferrous metal	66.7%
Nonferrous metal	8.4%
Rubber	0.7%
Paper	0.1%
Other	1.6%

When a white good is recycled, it is typically dismantled and/or shredded and divided into its component raw material types through a separation process. These recovered materials then enter their respective recovery streams. For example, the recovered steel from a refrigerator is processed along with other types of secondary steel to go into the production of new steel products.

The recovery of refrigerants associated with these appliances is not covered in this analysis. While these compounds can have significant GWPs, regulatory constraints and best practices limit their release to the atmosphere. The net GHG emission factors for the various waste management options for white goods are shown in Exhibit 7-7, and their derivation is discussed below.

Exhibit 7-7. GHG Emissions from MSW Management Options for White Goods (tonnes eCO₂/tonne)

	Net Recycling Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions
White Goods	(1.46)	NA	(0.26)	0.01

7.2.1 RECYCLING

Recycling white goods provides emission benefits through the recovery of raw materials that reduce the need for virgin (or primary) production of those materials. The GHG emissions benefits of recycling an “average” white good are presented in Exhibit 7-8.

Exhibit 7-8 Recycling Emissions for White Goods (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)
Management Option	Process Energy	Transportation Energy	Process Non-Energy	Net Emission Factor (=a + b + c)
Recycling	(1.34)	0.03	(0.15)	(1.46)

7.2.1.1 Open Loop Recycling

White goods are typically recycled in an open-loop scenario, i.e., when a white good is recycled, the raw materials do not necessarily become a new white good. As a result, the energy and GHG benefits associated with recycling a white good are based on the displacement of the manufacture of new raw materials that are a component of white goods. The recycling energy and GHG emission benefits of recycling white goods are a weighted average of the recycling energy and GHG emission benefits of recycling each of the raw material components of white goods – ferrous and nonferrous metals, and plastics. The process energy for the component material types was multiplied by the percent composition seen in Exhibit 7-6 to create a composite value representing a generic white good. For the plastic material within white goods, the average emission factor for all plastic types were calculated and multiplied by the percent composition. For non-ferrous metals in white goods, the average emission factor for copper wire and aluminum was calculated and multiplied by the percent composition. Details on the primary and secondary recycling processes for steel, aluminum, and copper wire are presented in Chapter 3 of this report.

Energy for transportation associated with the recycling of white goods is based on a composite of the transportation energy associated with recycling the various raw material components. A shredding and processing energy estimate of 680 MJ/tonne was also included by utilizing the shredding and processing energy estimate for electronics as a surrogate (Anonymous 2005). The recycling energy and GHG emission factors for white goods are presented in Exhibit 7-8.

7.2.2 COMBUSTION

The GHG emissions associated with combustion of white goods are estimated following the same approach used in estimating combustion emissions for electronics. Key materials are steel (typically recovered magnetically in the combustion process), and plastics (CO₂ emissions and electricity offsets in the waste-to-energy conversion). The results for each of the secondary products were weighted by the distribution shown in Exhibit 7-6. The combustion energy and GHG emission factors for electronics are presented in Exhibit 7-9.

Exhibit 7-9 Combustion Emissions for White Goods (tonnes eCO₂/tonne)

	(a)	(b)	(c)	(d)	(e)
Waste Management Option	Combustion Emissions	Transportation Energy	Avoided Utility Emissions	Avoided Emissions due to Steel Recovery	Net Combustion Emissions (=a + b - c - d)
Combustion	0.50	0.01	(0.03)	(0.74)	(0.26)

7.2.3 LIMITATIONS

The complexity of the white goods manufacturing and end-of-life system being simulated in this report presents several challenges with respect to localized variability and trans-boundary issues. The emission factors presented in this section represent average conditions that may not accurately characterize national or site-specific conditions. This is especially true for white goods, which are composites of multiple materials (e.g., steel, aluminum, and plastic) and are recycled through an open-loop scenario. For example, the raw material acquisition and manufacturing energy data for the component materials is based on Canadian and U.S. information (depending on the material). There is likely to be some variation between individual production facilities with respect to energy consumption efficiency and fuel type. In addition, because an overall average “white good” is modeled in this analysis, there is likely to be some raw material composition variation when compared to a specific type of white good (e.g., a refrigerator). Site-specific variability is also a concern with each of the end-of-life management options (e.g., transport distances). In addition, these values do not address international cross-border flows, which are quite significant for electronics recycling. While these limitations introduce uncertainty, the emission factors described herein provide a reasonable first-order estimate of the life-cycle GHG emissions associated with electronics recycling, landfilling, and combustion activities from a national average perspective.

8 Emission Factor Overview

The emission factors developed in the spreadsheet analysis and discussed throughout the previous overviews of the material types are calculated using the formula shown below.

Net GHG emissions = Gross GHG emissions - (Increase in carbon stocks + Avoided utility GHG emissions)

The results of this calculation, in tonnes of eCO₂ per tonne of waste, for each waste management strategy and material type are shown in Exhibit 8-1 and Exhibit 8-2. The exhibits are distinct based on differences in a key assumption: whether the effect of carbon sinks is included (Exhibit 8-1) or excluded (Exhibit 8-2) in the emission factor calculation. As discussed previously, this inclusion or exclusion has a significant effect on net emissions for the forest products and organic materials. It is important to note that the exhibits use the accounting convention that negative values reflect reductions in emissions and positive values reflect increases.

In order to apply the emission factors presented in this report, one must first establish two scenarios: (1) a baseline scenario that represents current management practices (e.g., disposing a tonne of newspaper per year in a landfill with national average characteristics in terms of LFG collection); and (2) an alternative scenario that represents the alternative management practice (e.g., recycling the same tonne of newspaper). The emission factors developed in this report then can be used to calculate emissions under both the baseline and the alternative management practices. Once emissions for the two scenarios have been determined, the next step is to calculate the difference between the alternative scenario and the baseline scenario. The result represents the GHG emission reductions or increases attributable to the alternative waste management practice.

As an example, assume that a town is trying to decide whether to combust or recycle a tonne of HDPE. A simple calculation using the emission factors from either of the exhibits (since carbon sinks have no effect on the emission factors for HDPE) indicates that combusting the HDPE would result in a net release of 2.85 tonnes of eCO₂, while recycling would result in negative net emissions of 2.27 tonnes of eCO₂. As a result, the overall effect of moving to an alternative scenario of recycling in comparison to a baseline of combustion would be $-2.27 - 2.85 = -5.12$ tonnes of eCO₂, i.e., an emission reduction of 5.12 tonnes of eCO₂.

Exhibit 8-1. GHG Emissions from Waste Management Options, with Carbon Sinks (tonnes eCO₂/tonne)

Material	Net Recycling Emissions	Net Composting Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE) - National Average	NLE Without Landfill Gas (LFG) Collection	NLE With LFG Collection and Flaring	NLE With LFG Collection and Energy Recovery
Newsprint	(2.75)	NA	(0.49)	(0.05)	(1.22)	(1.13)	(1.36)	(1.36)
Fine Paper	(3.20)	NA	(0.34)	(0.04)	1.18	1.71	0.31	0.28
Cardboard	(3.26)	NA	(0.32)	(0.04)	0.29	0.75	(0.48)	(0.51)
Other Paper	(3.27)	NA	(0.23)	(0.04)	0.71	1.19	(0.07)	(0.10)
Aluminum	(6.49)	NA	0.01	0.01	0.01	0.01	0.01	0.01
Steel	(1.18)	NA	0.01	(1.03)	0.01	0.01	0.01	0.01
Copper Wire	(4.10)	NA	0.01	0.01	0.01	0.01	0.01	0.01
Glass	(0.10)	NA	0.01	0.01	0.01	0.01	0.01	0.01
HDPE	(2.27)	NA	0.01	2.89	0.01	0.01	0.01	0.01
PET	(3.63)	NA	0.01	2.17	0.01	0.01	0.01	0.01
Other Plastic	(1.80)	NA	0.01	2.67	0.01	0.01	0.01	0.01
Food Scraps	NA	(0.24)	(0.10)	0.02	0.80	1.14	0.23	0.21
Yard Trimmings	NA	(0.24)	(0.15)	0.01	(0.33)	(0.17)	(0.60)	(0.61)
White Goods	(1.46)	NA	0.01	(0.26)	0.01	0.01	0.01	0.01
Personal Computers	(1.60)	NA	0.01	0.41	0.01	0.01	0.01	0.01
Televisions	(0.23)	NA	0.01	0.75	0.01	0.01	0.01	0.01
Microwaves	(1.27)	NA	0.01	(0.55)	0.01	0.01	0.01	0.01
VCRs	(0.95)	NA	0.01	0.15	0.01	0.01	0.01	0.01
Tires	(3.29)	NA	0.01	(0.49)	0.01	0.01	0.01	0.01

*The values shown for national average landfills are based on estimates of national average landfill gas collection and utilization rates.

Exhibit 8-2. GHG Emissions from Waste Management Options, Excluding Carbon Sinks (tonnes eCO₂/tonne)

Material	Net Recycling Emissions	Net Composting Emissions	Net Anaerobic Digestion Emissions	Net Combustion Emissions	Net Landfilling Emissions (NLE) - National Average	NLE Without Landfill Gas (LFG) Collection	NLE With LFG Collection and Flaring	NLE With LFG Collection and Energy Recovery
Newsprint	(0.30)	NA	(0.38)	(0.05)	0.23	0.32	0.09	0.08
Fine Paper	(0.36)	NA	(0.22)	(0.04)	1.35	1.88	0.48	0.45
Cardboard	(0.21)	NA	(0.20)	(0.04)	1.19	1.66	0.43	0.40
Other Paper	(0.25)	NA	(0.12)	(0.04)	1.22	1.70	0.44	0.40
Aluminum	(6.49)	NA	0.13	0.01	0.01	0.01	0.01	0.01
Steel	(1.18)	NA	0.13	(1.03)	0.01	0.01	0.01	0.01
Copper Wire	(4.10)	NA	0.13	0.01	0.01	0.01	0.01	0.01
Glass	(0.10)	NA	0.13	0.01	0.01	0.01	0.01	0.01
HDPE	(2.27)	NA	0.13	2.89	0.01	0.01	0.01	0.01
PET	(3.63)	NA	0.13	2.17	0.01	0.01	0.01	0.01
Other Plastic	(1.80)	NA	0.13	2.67	0.01	0.01	0.01	0.01
Food Scraps	NA	0.02	0.02	0.02	0.89	1.23	0.32	0.30
Yard Trimmings	NA	0.02	(0.04)	0.01	0.43	0.59	0.16	0.15
White Goods	(1.46)	NA	0.13	(0.26)	0.01	0.01	0.01	0.01
Personal Computers	(1.60)	NA	0.13	0.41	0.01	0.01	0.01	0.01
Televisions	(0.23)	NA	0.13	0.75	0.01	0.01	0.01	0.01
Microwaves	(1.27)	NA	0.13	(0.55)	0.01	0.01	0.01	0.01
VCRs	(0.95)	NA	0.13	0.15	0.01	0.01	0.01	0.01
Tires	(3.29)	NA	0.13	(0.49)	0.01	0.01	0.01	0.01

* The values shown for national average landfills are based on estimates of national average landfill gas collection and utilization rates.

Another perspective for viewing the emission factors is provided in Exhibit 8-3 and Exhibit 8-4 (which respectively include and exclude carbon sinks). These two exhibits allow the user to compare landfilling (the most common waste management method) with other methods. In these tables, the landfilling emission factors are based on national average conditions in terms of landfill gas collection and use for energy recovery. That is, 63 percent of landfilled waste is assumed to be disposed in landfills without gas recovery, 15 percent is destined for landfills that collect and flare the gas, and 23 percent is destined for landfills that use the gas for energy recovery. As is the case for the effect of carbon sinks, the assumptions on landfill gas affect the emission factors only for forest products and organics. An examination of Exhibit 8-1 through Exhibit 8-4 reveals several points:

- In general, recycling reduces GHG emissions relative to landfilling. The emission reductions, on a per tonne basis, are quite significant in some cases.
- The effect of including or excluding carbon sinks has an important effect on the results for paper, food scraps, and yard trimmings. For comparisons between combustion and landfilling for newsprint and yard trimmings, it changes the sign from positive (combustion increases emissions when carbon sinks are included) to negative (combustion decreases emissions when carbon sinks are excluded). This is particularly evident for newsprint, which has a large landfill carbon storage factor.
- On a per-ton basis, the metals (aluminum, copper wire, steel), paper, plastic, and several of the composite materials (PCs, microwaves, white goods), and tires have the greatest magnitude of negative net emissions through recycling, due primarily to reductions in energy use in the raw material acquisition and manufacturing step and (for paper) forest carbon sinks.
- For metals and glass bottles, there is almost no distinction in GHG emissions between any of the “downstream” waste management methods, i.e., landfilling, combustion, anaerobic digestion, and composting – with the exception of steel combustion.³⁰ For the other materials – paper, plastics, organics, electronics, and tires – the choice of management method can have significant implications.
- The emissions factors for the landfilling of paper and organics are quite sensitive to whether the landfill has a gas collection system (and to a lesser extent, whether gas capture is accompanied by flaring or by energy recovery).

³⁰ Steel is an exception because GHGs are reduced when steel is recovered from combustion facilities.

Exhibit 8-3. GHG Emissions from MSW Management Options Compared to Landfilling* (option's net emissions minus landfilling net emissions), Including Carbon Sinks (tonnes eCO₂/tonne)

Material	Recycling	Composting	Anaerobic Digestion	Combustion
Newsprint	(1.53)	NA	0.72	1.16
Fine Paper	(4.38)	NA	(1.52)	(1.22)
Cardboard	(3.54)	NA	(0.60)	(0.33)
Other Paper	(3.98)	NA	(0.95)	(0.75)
Aluminum	(6.51)	NA	(0.00)	(0.00)
Steel	(1.20)	NA	(0.00)	(1.04)
Copper Wire	(4.11)	NA	(0.00)	(0.00)
Glass	(0.12)	NA	(0.00)	(0.00)
HDPE	(2.29)	NA	(0.00)	2.87
PET	(3.64)	NA	(0.00)	2.15
Other Plastic	(1.82)	NA	(0.00)	2.65
Food Scraps	NA	(1.04)	(0.90)	(0.78)
Yard Trimmings	NA	0.09	0.18	0.34
White Goods	(1.48)	NA	(0.00)	(0.27)
Personal Computers	(1.61)	NA	(0.00)	0.40
Televisions	(0.24)	NA	(0.00)	0.73
Microwaves	(1.28)	NA	(0.00)	(0.56)
VCRs	(0.97)	NA	(0.00)	0.14
Tires	(3.31)	0.00	(0.00)	(0.50)

*The values shown for landfills are based on estimates of national average landfill gas collection and utilization rates.

Exhibit 8-4. GHG Emissions from MSW Management Options Compared to Landfilling* (option's net emissions minus landfilling net emissions), Excluding Carbon Sinks (tonnes eCO₂/tonne)

Material	Recycling	Composting	Anaerobic Digestion	Combustion
Newsprint	(0.53)	NA	(0.34)	(0.28)
Fine Paper	(1.71)	NA	(1.69)	(1.39)
Cardboard	(1.41)	NA	(1.42)	(1.23)
Other Paper	(1.47)	NA	(1.44)	(1.26)
Aluminum	(6.51)	NA	(0.00)	(0.00)
Steel	(1.20)	NA	(0.00)	(1.04)
Copper Wire	(4.11)	NA	(0.00)	(0.00)
Glass	(0.12)	NA	(0.00)	(0.00)
HDPE	(2.29)	NA	(0.00)	2.87
PET	(3.64)	NA	(0.00)	2.15
Other Plastic	(1.82)	NA	(0.00)	2.65
Food Scraps	NA	(0.86)	(0.98)	(0.87)
Yard Trimmings	NA	(0.41)	(0.42)	(0.42)
White Goods	(1.48)	NA	(0.00)	(0.27)
Personal Computers	(1.61)	NA	(0.00)	0.40
Televisions	(0.24)	NA	(0.00)	0.73
Microwaves	(1.28)	NA	(0.00)	(0.56)
VCRs	(0.97)	NA	(0.00)	0.14
Tires	(3.31)	NA	(0.00)	(0.50)

*The values shown for landfills are based on estimates of national average landfill gas collection and utilization rates.

The use of the different waste management strategies discussed throughout this report is associated with varying levels of energy use. Exhibit 8-5 summarizes the amount of energy that is consumed by each waste management strategy for the management of one tonne of each material type. Note that this exhibit does not differentiate between different types of energy (i.e., 1 GJ of fossil fuel-derived energy counts exactly as much as 1 GJ of renewable energy in this tabulation). The arithmetic of applying these energy factors is the same as for the GHG emission factors. For example, if a municipality wished to determine the energy implications of recycling instead of landfilling a tonne of steel, the calculation would start with the baseline (landfill) energy use of 0.15 GJ; recycling results in an energy credit (i.e., negative net use) of -12.47 GJ; thus, the overall effect of moving to an alternative scenario of recycling in comparison to a baseline of combustion would be $-12.47 \text{ GJ} - 0.15 \text{ GJ} = -12.61 \text{ GJ}$, i.e., a reduction in energy use of 12.61 GJ.

In examining these energy factors, it may again be useful to compare landfilling (as the most common waste management method) with other methods. Exhibit 8-6 provides this comparison, showing the delta between energy use for all other waste management methods with respect to the energy use factors for national average landfill conditions.³¹ Like the effect of carbon sinks, the assumptions on landfill gas affect the emission factors only for forest products and organics.

Inspecting Exhibit 8-5 and Exhibit 8-6 raises several points, which are discussed below.

- Recycling of both metals and plastics is associated with relatively high energy consumption benefits.
- The impact of landfill gas recovery and energy generation is clearly evident when comparing landfill disposal for forest products and organics. Fine paper in particular has nearly a 1 GJ/tonne differential when comparing landfills with and without landfill gas collection and energy generation.
- The combustion of steel presents some energy benefits due to the recovery of ferrous materials at the combustion facility and subsequent recycling of the material.

In closing, it is important to reiterate that users of the emission factors and energy factors should beware of the caveats and limitations that have appeared throughout this report. Although the analysis is based on the best available data collected within the time and resource constraints of

³¹ Note that energy recovery of LFG has a slight effect on net landfill energy, so the net energy value is a function of the proportion of landfilled waste disposed at landfills with energy recovery (23 percent) versus no energy recovery (77 percent).

the project, and assumptions believed to be reasonable, the accuracy of the analysis is limited by the use of these assumptions and limitations in the data sources. Where possible, the emission factors reported here can be improved by substituting process- or site-specific data to increase the accuracy of the estimates. Despite the uncertainty in the emission factors, they provide a reasonable first approximation of the GHG impacts of solid waste management, and that they provide a sound basis for evaluating voluntary actions to reduce GHG emissions in the waste management arena.

Exhibit 8-5. Energy Impacts from MSW Management Options (GJ/tonne)

	Net Recycling Energy Use	Net Anaerobic Digestion Energy Use	Net Combustion Energy Use	Net Landfilling Energy (NLE) Use - National Average	NLE Without Landfill Gas (LFG) Collection	NLE With LFG Collection and Flaring	NLE With LFG Collection and Energy Recovery
Newsprint	(6.33)	(0.78)	(2.62)	0.11	0.15	0.15	(0.00)
Fine Paper	(15.87)	(2.49)	(2.23)	(0.06)	0.15	0.15	(0.78)
Cardboard	(8.56)	(1.71)	(2.31)	(0.04)	0.15	0.15	(0.67)
Other Paper	(9.49)	(1.66)	(2.25)	(0.04)	0.15	0.15	(0.68)
Aluminum	(87.22)	0.11	0.22	0.15	0.15	0.15	0.15
Steel	(12.47)	0.11	(10.82)	0.15	0.15	0.15	0.15
Copper Wire	(71.56)	0.11	0.20	0.15	0.15	0.15	0.15
Glass	(1.54)	0.11	0.19	0.15	0.15	0.15	0.15
HDPE	(64.27)	0.11	(6.30)	0.15	0.15	0.15	0.15
PET	(85.16)	0.11	(3.22)	0.15	0.15	0.15	0.15
Other Plastic	(52.09)	0.11	(4.76)	0.15	0.15	0.15	0.15
Food Scraps	N/A	(1.69)	(0.71)	0.01	0.15	0.15	(0.45)
Yard Trimmings	N/A	(0.70)	(0.86)	0.08	0.15	0.15	(0.14)
White Goods	(23.70)	0.11	(8.52)	0.15	0.15	0.15	0.15
Personal Computers	(20.11)	0.11	(3.21)	0.15	0.15	0.15	0.15
Televisions	(1.22)	0.11	(2.12)	0.15	0.15	0.15	0.15
Microwaves	(13.73)	0.11	(8.64)	0.15	0.15	0.15	0.15
VCRs	(10.62)	0.11	(5.92)	0.15	0.15	0.15	0.15
Tires	0.00	0.11	(0.39)	0.15	0.15	0.15	0.15

* The values shown for national average landfills are based on estimates of national average landfill gas collection and utilization rates.

Exhibit 8-6. Energy Impacts from MSW Management Options Compared to Landfilling*
 (option's net emissions minus landfilling net emissions) (GJ/tonne)

	Recycling	Anaerobic Digestion	Combustion
Newsprint	(6.45)	(0.90)	(2.74)
Fine Paper	(15.81)	(2.43)	(2.17)
Cardboard	(8.52)	(1.68)	(2.27)
Other Paper	(9.45)	(1.62)	(2.20)
Aluminum	(87.36)	(0.04)	0.07
Steel	(12.61)	(0.04)	(10.97)
Copper Wire	(71.71)	(0.04)	0.05
Glass	(1.68)	(0.04)	0.04
HDPE	(64.42)	(0.04)	(6.45)
PET	(85.31)	(0.04)	(3.37)
Other Plastic	(52.24)	(0.04)	(4.91)
Food Scraps	NA	(1.70)	(0.72)
Yard Trimmings	NA	(0.78)	(0.94)
White Goods	(23.85)	(0.04)	(8.67)
Personal Computers	(20.26)	NA	(3.36)
Televisions	(1.37)	NA	(2.27)
Microwaves	(13.88)	NA	(8.79)
VCRs	(10.77)	NA	(6.07)
Tires	(0.15)	NA	(0.54)

*The values shown for landfills are based on estimates of national average landfill gas collection and utilization rates.

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10 Glossary

Biomass: Comprises the mass of all living biological organisms, dead or alive. This term often refers to vegetation (which composes the majority of biomass in all ecosystems).

Centralized composting: Involves the collection and transportation of organic materials to a special facility where it will be prepared and processed into compost.

Composting: A natural process whereby micro-organisms transform organic waste materials into a soil-like product. Kitchen scraps, leaves and yard waste, paper, wood, food-processing wastes, as well as agricultural crop wastes and animal manures, are excellent inputs for composting.

Combustion: Refers to controlled burning of waste, in which heat chemically alters organic compounds, converting into stable inorganics such as carbon dioxide and water.

Energy from Waste facilities (EFW): These facilities incinerate solid waste to produce heat and generate electricity.

Institutional, commercial, and industrial (IC&I) waste: Includes materials from sources such as heavy and light industry, manufacturing, warehousing, transportation, retail and wholesale commercial activities, restaurants, offices, educational or recreational facilities, health and other service facilities.

Landfills: Disposal sites for non-hazardous solid wastes spread in layers, compacted to the smallest practical volume, and covered by material applied at the end of each operating day. Secure chemical landfills are disposal sites for hazardous waste, selected and designed to minimize the chance of release of hazardous substances into the environment.

“Other” Paper: Defined as 5% Newsprint, 60% fine paper, 30% cardboard, 5% coated paper. This material type category can include bags and sacks, other paper packaging, books, other paperboard packaging, wrapping papers, paper plates and cups, folding cartons, other non-packaging paper, and tissue paper and towels.

TeraJoules (TJ): The meter-kilogram-second unit of work or energy; one joule is equal to the work done by a force of one Newton when its point of application moves through a distance of one meter in the direction of the force. TeraJoules are equal to Joules x 10^{12} .

Materials recovery facility (MRF): A facility that processes residentially collected mixed recyclables into new products available for market.

Post-consumer: Recycled material that is recovered after consumer use (e.g., aluminum from a used beverage can).

Recovery: Reclaiming of recyclable components and/or energy from the post-collection solid waste stream by various methods including but not limited to manual or mechanical sorting, incineration, distillation, gasification, or biological conversion other than composting.

Recyclable: refers to a product or substance that can be diverted from the solid waste stream through a widely available and economically viable collection, processing and marketing system, and used in the manufacture of a new product.

Recycling retention rate: This is the rate of recovered materials that makes it into a new product after processing losses at the recovery facility and manufacturing plant.

Recycling: The process whereby a material (e.g., glass, metal, plastic, paper) is diverted from the waste stream and remanufactured into a new product or is used as a raw material substitute.

Waste: All materials unwanted by their generator. This includes all low value materials that are intended for recycling, treatment or disposal that are removed without, or with only nominal, remuneration to the waste generator.

Appendix A. Provincial Electricity Generation

This appendix presents the results of a research effort to expand the scope and flexibility of electricity and fuel intensity factors that serve as inputs to the analysis of GHG emissions resulting from waste management activities in Canada. A range of electricity emission factors – including Canadian national average, provincial production-weighted average (or “custom”), U.S. national average, and those focusing on incremental electricity use at the margin – are the focus of the current analysis. ICF has enhanced its analytical approach to accommodate “toggling” which set of assumptions to use for manufacturing and energy offset calculations.

The improvements to the original data set allow for sensitivity analysis of the importance of electricity-related emissions for all of the materials (including aluminum, for which the original report assumed 100% hydropower), and facilitate potential analysis of transboundary effects by providing the flexibility to compare Canadian and U.S. results using consistent factors. In all cases, the effect of using different values will be to vary the GHG emissions associated with electricity use throughout the (expanded) life cycle of a given material. The newly expanded data differ from those used in the earlier study in that they (1) reflect updated data on fuel mixes (both at the provincial and national level), (2) provide a U.S. average value for use in potential analyses of transboundary effects, (3) the production-weighted values incorporate new information on production, by province, and (4) include “pre-combustion” emissions associated with fossil fuels, i.e., the emissions associated with extracting and processing natural gas, oil, and coal prior to their combustion at a power generator.

Below, these additions to the analysis are discussed – emission factors and energy factors – and how they are being incorporated into the revised spreadsheet workbook. This appendix is organized as follows:

- Section 1 presents Canadian province-specific and national average electricity emission factors
- Section 2 describes the derivation of the “custom,” i.e., production-weighted, average electricity emission factors
- Section 3 describes the U.S. average electricity emission factor
- Section 4 describes the marginal emission factor.

The emission factors presented in each section have been calculated based on data on emissions and electricity use in 2003. Expressed in units of grams of eCO₂ per kilowatt-hour of electricity use, they include estimates of CO₂, CH₄, and N₂O from Canadian power plants. Two sets of factors are provided – one for which only the GHG emissions at the power plants are included, and a second set in which the pre-combustion emissions associated with the production of the power plant fossil fuels are also included.

1 Provincial and National Average Electricity Coefficients

This section describes the derivation of provincial and national average electricity emission factors. Exhibit A-1 displays the factors, both with and without the effect of including pre-combustion emissions, for each province and the entire country.

Exhibit A-1. 2003 GHG Electricity Emission Factors (g eCO₂ / kWh)

Province	Power Plant Emissions Excluding Pre-combustion	Power Plant Emissions Including Pre-combustion
Nfld	152	187
P.E.I.	488	559
N.S.	642	670
N.B.	468	532
PQ	8	10
ON	309	320
MAN	76	76
SASK	860	888
ALTA	1,009	1,038
B.C.	24	28
Yukon	38	47
N.W.T.	399	487
Nunavut ³²	269	281
Canada	269	281

1.1 Key Data Sources and Assumptions

Power Plant Fuel Consumption is derived from Statistics Canada, “Report on Energy Supply-Demand in Canada, Catalogue no. 57-003-XIB”. The conversion factors from this source were also used to convert between physical and natural units when working with the energy and emissions data.

Emission Factors for fuel combustion were obtained from the Climate Change Technology Early Action Measures (TEAM), TEAM (2002).

Pre-combustion “Adders” for fossil fuels (i.e., factors to account for emissions upstream of the point of combustion) are documented below. The adders are 9.9 kg eCO₂ per GJ of natural gas

³² Note that in the case of Nunavut, the Canadian coefficient is listed. The concept of a single grid factor does not apply very well for Nunavut, where isolated diesel generators are the primary mode of generation. The total quantities of electricity from Nunavut that factor into downstream numbers for emissions embodied in waste are very small, and emissions of Nunavut electricity generation are not relevant to the results of this analysis.

consumed, 17.8 kg eCO₂ per GJ of petroleum fuel consumed, and 6.4 kg eCO₂ per GJ of coal consumed.

U.S. Electricity Emission Factor, where the method required the application of an average end use emission factor for U.S. electricity to address imports, a value of 668 grams per kilowatt-hour was used. Note that subsequent investigation of the U.S. average factor has resulted in development of a slightly different factor for U.S. electricity, as described in section 4 of this appendix.

1.2 Background and Method

In the method used here, end use emission factors are developed using Statistics Canada's Report on Energy Supply-Demand in Canada, Catalogue no. 57-003-XIB, reference year 2003. (STATCAN 2003) as the primary data source for electricity consumption and power plant inputs, and using Environment Canada's emission factors for the power plant input fuels. As the mix of power plant fuels changes, the end use emission factors also change. Ideally, models for computing the GHG benefits of waste management options would contain a set of electricity emission factors for each year, and the user would be required to specify the year in which electricity use occurs so that the appropriate emission factors could be applied. For previous projects, Torrie-Smith Associates has developed end use electricity emission factors for Canada for 1990 forward, but they do not change very dramatically from year-to-year, and for the current task of estimating the GHG impacts of electricity savings that result from waste reduction and recycling, it is sufficient to employ a single set of factors for a recent, typical year. The factors presented here have been updated to the year 2003, the most recent year for which the data are available for the calculations.

1.3 General Method Used to Produce End Use Emission Factors for Electricity

Essentially, the method employed involves computing the GHG emissions from the power plant inputs in each province, and dividing that number by the "final demand" for electricity in that province, with the resulting emission factor being presented in grams of eCO₂ per kilowatt-hour delivered. Emissions are based on the fuels used as power plant inputs by both industry and utilities, as reported in Statistics Canada Report on Energy Supply-Demand in Canada, Catalogue no. 57-003-XIB, reference year 2003 (STATCAN 2003). The emissions are pro-rated over "Energy Use – Final Demand" from that same publication.³³ The computation includes an adjustment for international and inter-provincial flows of electricity, as described in more detail below.

³³ Industrial cogeneration will be reflected in the emissions and the final demand for electricity data used in these calculations to the extent the data is included in the Report on Energy Supply-Demand in Canada (Statistics Canada, Catalogue 57-003-XIB). In the case of the fuel inputs to industrial cogeneration, these are at least partly included in Table 1, Line 11 of Statistics Canada Catalogue 57-003-XIB. In the case of the electricity output from cogenerators, it is partly included in the Final Demand (Line 18) of the Electricity Column, but the proportion is not specified.

An emissions coefficient is calculated for each province, for Canada, and for the United States. The Canadian coefficient is used for electricity flowing into a Canadian province from another Canadian province where the originating province or generating site for the electricity cannot be readily identified. In most cases, however, the originating province can be identified and the appropriate provincial electricity coefficient is used. The average U.S. coefficient is used for international imports of electricity to Canadian provinces, with the exception of international flows into British Columbia, which are assumed to be from hydroelectric sites on the Columbia River Basin in the U.S. Pacific Northwest.

Final emissions coefficients are a blend of emissions coefficients from intra-provincial generation of electricity, inter-provincial net inflows (called interregional transfers or IRTs) and international imports from the United States. Provinces that import electricity from the United States are usually net international exporters, but the imports are in some cases substantial and so they are counted as contributors to the province’s energy supply. The origins of inter-provincial inflows of electricity are often clear, as in the case of Quebec’s imports of electricity from Churchill Falls, Labrador. In these circumstances, the emissions coefficient assigned to these inflows of electricity are those of the originating province, or, as in the case of Churchill Falls, the originating generating site.

Final demand for electricity is total electric power production, plus net imports and inter-regional transfers, minus producer consumption. In circumstances where there are inter-provincial inflows of electricity or international imports, a prorated share of producer consumption is assigned to each source of electricity. This is done to take line losses into account for all sources of electricity, and not just intra-provincial electricity generation.

All data on primary and secondary electricity production, international imports, interregional transfers, and producer consumption are taken from Statistics Canada’s Report on Energy Supply-Demand in Canada, Catalogue no. 57-003-XIB. Electricity generated by industry is included in the calculation of emissions coefficients. Industrial generation is generally very small compared to utility generation, and so has only a minor effect on the provincial coefficients.

Regarding Labrador The Newfoundland average coefficient is not appropriate for use in Labrador, where communities will in general either be connected to the Labrador grid – in which case a zero coefficient may be used for electricity reflecting its nearly 100% hydroelectric content – or they will be utilizing power from diesel powered generators not connected to the grid, in which case their emissions will be very much higher than the Newfoundland average coefficient. In such cases, including for remote communities in other parts of Canada that are isolated from the grid and using diesel generation, it is recommended that the provincial coefficient be overwritten. For grid-isolated diesel generation, the following values are recommended. They are based on diesel generators that deliver electricity to end-users with a net efficiency from fuel to end use of 27%.

Carbon dioxide:	0.940 kg per kWh
Methane:	0.0001378 kg per kWh
Nitrous Oxide (N2O):	0.0000896 kg per kWh

Note that these factors, while available for use in special applications, are not incorporated into the defaults currently programmed into the spreadsheet workbook.

1.4 Pre-Combustion Adders

Just as the life cycle includes raw material acquisition for the materials used in production (e.g., the wood used to make paper, or the bauxite used to make aluminum), there is also a “raw material acquisition” aspect to the fossil fuels used to supply energy throughout the life cycle.

Examples of these pre-combustion emissions include CH₄ emitted from natural gas pipelines used to transport gas and CO₂ emitted from burning fuel in the engines that drive oil wells.

Separate factors for petroleum, natural gas, and coal were developed. In all three cases, the pre-combustion emissions are a significant proportion of the emissions at the point of combustion, and thus this addition to the life cycle has a significant effect on the overall emissions picture.

1.4.1 PETROLEUM AND NATURAL GAS

The pre-combustion emission factors for petroleum and natural gas were derived from information in the *2001 Greenhouse Gas Emissions Inventory Summary for Canada EC (2002)* and information from Statistics Canada, Report on Energy Supply-Demand in Canada, Catalogue no. 57-003-XIB. (STATCAN 2003). Basically, the emissions by output was divided to develop a pre-combustion emission factor for both petroleum and natural gas. The main issues involved in developing these factors were determining which emissions should be included, and how to allocate them to either petroleum or gas (as a practical matter, gas and oil are extracted and processed in many of the same steps).

Data on emissions associated with the production, refining and transportation of natural gas and petroleum in Canada are taken from the national GHG inventory and include the energy-related emissions of the oil and gas industry, the energy-related emissions of the petroleum refining industry, the energy-related emissions of pipeline energy use, and the fugitive emissions from oil and gas production.

For production of natural gas the 2001 value for natural gas of 6,500,000 TJ was used, and total refined petroleum product (RPP) production of 3,700,000 TJ was used, yielding a ratio of gas to RPP output of 64:36. This ratio was used to apportion emissions from the sectors that pertain to both natural gas and RPP, viz. fossil fuel production, pipelines, venting, and flaring.

The final step in the calculation was to divide the appropriate share of the fossil fuel GHG emissions by the natural gas and RPP output values, in order to get the pre-combustion factor. These factors are 9.9 kg eCO₂ per GJ of natural gas, and 17.8 kg eCO₂ per GJ of RPP. The RPP value is assumed to apply to diesel, heavy fuel oil, light fuel oil, and LPG (liquefied petroleum gas).

1.4.2 COAL

The pre-combustion emission factor for coal is 6.42 kg eCO₂ per GJ of coal, and was obtained from U.S. EPA's Fuel Life Cycle Emissions Model (FULCEM), developed based on life cycle data provided by Franklin Associates. The model, which provides emissions associated with individual life-cycle elements for fuels, is currently in draft form, is based on U.S. data, and is not publicly available. A source of Canadian data on energy used in coal mining and processing was not found.

1.5 Province-Specific Notes

Information specific to each of the ten major consuming province's calculated emissions coefficients is presented in the paragraphs below.

Newfoundland and Labrador Because of Newfoundland's large-scale exports of Churchill Falls hydroelectric power to Quebec, Churchill Falls power has been excluded from the calculation of the province's electricity emissions coefficient. Churchill Falls production was subtracted from total Newfoundland and Labrador hydro production. Producer consumption (shown in Statistics Canada, Report on Energy Supply-Demand in Canada, Catalogue no. 57-003-XIB) (STATCAN 2003) was prorated between Churchill Falls electricity production and the remaining provincial electricity production. The prorated non-Churchill Falls producer consumption was then subtracted from non-Churchill Falls production to arrive at an estimate of final demand for electricity for the Island of Newfoundland. The emissions coefficient is then calculated by dividing total emissions from power production by final demand for electricity.

Prince Edward Island P.E.I. imports almost all of its power from New Brunswick and its emissions are therefore largely determined by the New Brunswick emission coefficient. Producer consumption of electricity in PEI, including line losses, is pro-rated between the Island and mainland sources.

Quebec Quebec imports significant amounts of electricity from Labrador. Imports from Labrador are assumed to be exclusively from the Churchill Falls hydroelectric site, and so are assigned a zero emissions coefficient. Quebec also imports small amounts of electricity from the United States (although it is by far a net exporter of electricity to the United States). These imports are assigned an average U.S. emissions coefficient. The majority of Quebec's electricity is generated within the province, and is assigned an emissions coefficient based on the province's generating mix (almost exclusively hydro, with some nuclear). The final emissions coefficient is a prorated blend of the emissions coefficients of Quebec, interregional imports and international imports from the United States. Emissions coefficients from these different sources are prorated based on their relative contribution to final demand for electricity.

It is important to note that in hydro-dominated systems like Quebec, Manitoba, and British Columbia, the percent variation in the end use emission factor may be very large from year to year. In provinces where fossil fuel generation is a very small contributor to production, the average emission factor for the province will be very small, but it can change by a factor of two or more from year to year as the use of the fossil plants goes up and down.

Ontario Electricity imported from Manitoba is assigned that province's electricity coefficient. Electricity imports from the United States are assigned an average U.S. emissions coefficient. The majority of Ontario's electricity is generated within the province, and is assigned an emissions coefficient based on the province's generating mix. The final emissions coefficient is a prorated blend of the emissions coefficients of Ontario, interregional imports and international imports from the United States. Emissions coefficients from these different sources are prorated based on their relative contribution to final demand for electricity.

Manitoba Manitoba exports significant amounts of electricity, primarily to the United States and Ontario. It also imports a small amount of electricity from the United States. Electricity imported from the United States is assigned an average U.S. emissions coefficient. The majority of Manitoba's electricity is generated within the province, and is assigned an emissions coefficient based on the province's generating mix (primarily hydroelectric). The final emissions coefficient is a prorated blend of the emissions coefficients of Manitoba and international imports from the United States. Emissions coefficients from these sources are prorated based on their relative contribution to final demand for electricity.

Northwest Territories, Nunavut, and Yukon. There are no interregional transfers of electricity into or out of the Northwest Territories, Nunavut, or Yukon and so the electricity emission factors for these jurisdictions are based solely on their own power plants. Also, the same pre-combustion adders are used for power plant fuels in these northern areas as for the rest of the country; no special allowance is made for the longer distances over which fuels must be transported to the northern power plants. These parts of Canada do not have the type of integrated grid that exists in the southern provinces, and it is not as useful to develop a "province wide" emission factor for electricity. There is widespread use of fossil-fired, isolated generator sets (mostly diesel fueled) in which case end use factors should be based on emission profile and distribution characteristics of the local electricity supply situation. In the case of Nunavut, the Canadian emission factor as the input data did not support the full application of our method. In any event, the emissions from electricity production in the Northwest Territories, Nunavut, and Yukon have almost no impact on the calculation of embodied electricity and emissions done for this analysis.

2 Production-weighted Electricity Coefficients

This section describes the derivation of "custom" electricity emission factors in which emission intensity factors are distributed for each material according to the location of manufacturing plants. The method employed is similar to that used to estimate the electricity coefficients used in the original analysis; however both the provincial electricity emission factors and production distribution data have been revised.

2.1 Key Data Sources and Assumptions

Provincial electricity emission factors, as described above, are the basis of the custom factors.

Provincial distribution of material production provides the basis for weighting the above factors. These distributions are presented below, in percentage terms, in Exhibit A-2 and Exhibit A-3, and show the underlying data behind the distributions. For the four paper types, aluminum, and steel, the provincial distribution is based on production capacities by material, with data obtained from the Pulp and Paper Research Institute of Canada (1993), the Aluminum Association of Canada, and a report developed for NRCan by MK Jaccard and Associates and Willis Energy Services Ltd. (1996). Since production capacities were not readily available for glass bottles and plastics, these distributions were based on the number of manufacturing facilities in each

province, obtained from Statistics Canada. In other words, it was assumed that production (or more precisely, electricity consumption) is proportional to the number of establishments.

For all materials except steel, information distinguishing the provincial distributions of virgin (primary) versus recycled production was not found. Thus, except for steel, the provincial distributions for each material are assumed to be the same for virgin and recycled production. For steel, the distribution of virgin production is based on the production capacities for integrated Canadian steel mills, all of which operate in Ontario. The distribution of recycled-production steel is based on the production capacities at Canadian electric arc furnace plants.

Exhibit A-2. Production Distribution by Province

Province	Newsprint	Fine Paper	Cardboard	Other Paper	Aluminum	Steel – Virgin Product	Steel – Recycled Product	Glass	Plastics
NF	5%	0%	0%	0%	0%	0%	0%	0%	1%
PE	0%	0%	0%	0%	0%	0%	0%	0%	0%
NS	12%	0%	2%	8%	0%	0%	10%	0%	0%
NB	5%	16%	0%	4%	0%	0%	0%	2%	1%
PQ	36%	37%	56%	33%	90%	0%	34%	28%	26%
ON	16%	24%	38%	45%	0%	100%	32%	39%	48%
MB	2%	0%	0%	3%	0%	0%	5%	0%	3%
SK	0%	7%	0%	0%	0%	0%	12%	1%	1%
AB	0%	0%	0%	0%	0%	0%	7%	10%	8%
BC	24%	15%	3%	7%	10%	0%	0%	20%	11%
Yukon	0%	0%	0%	0%	0%	0%	0%	0%	0%
N.W.T.	0%	0%	0%	0%	0%	0%	0%	0%	0%
Nunavut	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Exhibit A-3. Derivation of Provincial Production Distribution

Province	Production Capacity							Number of Manufacturing Establishments	
	Newsprint (tonnes/day)	Fine Paper (tonnes/day)	Cardboard (tonnes/day)	Other Paper (tonnes/day)	Aluminum (tonnes/year)	Steel – Virgin Product (megatonnes/year)	Steel – Recycled Product (megatonnes/year)	Glass	Plastics
NF	1,622								11
PE									4
NS	3,765		193	1,014			0.6	1	32
NB	1,634	1,300		461				2	25
PQ	11,334	3,049	4,589	4,236	2,436,000		2.2	30	523
ON	5,198	1,986	3,103	5,726		9.2	3.6	42	986
MB	487			420			0.3		61
SK		609					0.9	1	30
AB							0.3	11	163
BC	7,676	1,226	261	890	274,000			22	232
Yukon									
N.W.T.									
Nunavut									
Total	31,716	8,170	8,146	12,747	2,710,000	9.2	7.9	109	2,076

Production capacity source for paper: Pulp and Paper Research Institute of Canada (1993)

Production capacity source for aluminum: Aluminum Association of Canada (2004)

Production capacity source for steel: MK Jaccard and Associates and Willis Energy Services Ltd. (1996)

Statistics Canada, Annual Survey of Manufactures, CANSIM table 301-0003"

Number of production facilities source for steel: Steel Association of Canada (2004)

2.2 Background and Method

The provincial average electricity emission factors (described in section 2 of this addendum) are weighted according to the estimated geographic distribution of production for each material. The average custom electricity emission factor for a particular manufactured good, M, is estimated according to the formula below:

$$\sum_{P=1}^{13} EF_P \bullet Share_{P,M}$$

Here, the products of the average provincial emission factor (EF, as estimated in section 2) and provincial share of manufacturing specific to M are summed across all 13 provinces included in the analysis for each M.

3 Transboundary Effects: U.S. Electricity Factors

The emission factors developed for the original report were based on the assumption that material recycled in Canada displaces or impacts Canadian production facilities, i.e. that materials diverted in Canada are also remanufactured in Canada. However, this is not entirely the case. In fact, Canada has large trade flows of recyclables – both imports and exports – with the United States, China, India, and potentially other trading partners. For many of the most emission-intensive pre-consumer life-cycle elements, the emission effects occur remotely. Moreover, emission factors for economies with more carbon-intensive industrial and electric utility sectors (e.g., for the United States) are quite different from those for Canada. Thus, to neglect exports (and imports) as in the previous report is not necessarily accurate.

For purposes of conducting screening analyses of transboundary effects, the U.S. average electricity emission factor is included in the spreadsheet workbook. The incorporation of the U.S. average electricity emission factor should facilitate analysis of transboundary effects by providing the flexibility to compare Canadian and U.S. results using consistent factors, or to assign the U.S. electricity emission factor for certain stages of the life cycle (e.g., remanufacturing of aluminum cans).

3.1 Key Data Sources and Assumptions

CO₂ emissions from the electric power sector in 2001 were obtained from EIA's *Electric Power Annual 2002 EIA(2002a)*.

CH₄ and N₂O emissions from the electric power sector in 2001 were obtained from EIA's *Emissions of Greenhouse Gases in the United States 2002 EIA (2002b)*.

Total U.S. retail sales of electricity (MWh) in 2001 was obtained from EIA (2002a).

3.2 Background and Method

The estimated emission factor for U.S. electricity use in 2001 was derived using a similar approach, but different data sources from those described above for Canadian electricity use. The estimation method involved dividing total national GHG emissions from the electric power sector (including CO₂, CH₄, and N₂O) by total national electricity purchases (i.e., delivered electricity). This results in a general, average emission factor applicable nationally. All emissions were converted to CO₂ equivalent units using their respective global warming potentials (GWPs). The result of the calculation is a value of 680 gm eCO₂ / kWh, excluding the effect of pre-combustion emissions.

4 Marginal Electricity Coefficient

All of the coefficients presented above apply as average factors, incorporating the full array of fuels consumed in power generation. The final option available to users of the current spreadsheet workbook is that of the marginal electricity coefficient. This additional option allows for a user to select a marginal factor, based on the last unit of fuel added to the supply curve. The underlying rationale for choosing an approach where emissions are based on the marginal fuel is that much of the “zero-emission” generation capacity is essentially constant; e.g., once a utility has constructed a nuclear plant or a hydropower facility, they will run that unit at full capacity (because the costs are largely capital costs), and that additional power “at the margin” is likely to be fossil based (where a significant portion of the cost of generation is associated with the fuel itself). In the original report, an electricity emission factor based on marginal fuel use was used exclusively for energy offsets associated with energy recovery from landfill gas or waste combustion. Specifically, it was assumed that all offsets would displace gas-fired integrated gas combined cycle (IGCC) units.

In the current approach, it is again assumed that the fuel “at the margin” will always be natural gas, and the option to use this marginal factor is extended to the upstream calculations as well. In accordance with the National Climate Change Plan, a carbon content of 48.8 kg e CO₂/GJ, 50% generation efficiency, and 10% transmission and distribution loss, resulting in an end use marginal electricity emission factor of 108 kg eCO₂/Gj delivered electricity were assumed. Including “pre-combustion” emissions associated with natural gas extraction, processing, and transport, the factor is 136 kg eCO₂/GJ delivered electricity.

Appendix B: Background Tables

Exhibit B-1 2001 GHG Emissions Associated with the Production, Refining, and Transportation of Natural Gas

Category	Sources	Emissions from Natural Gas and RPP Production ¹			Percent Attributable to Natural Gas Production ²	Emissions from Natural Gas Production ³			Energy Use by Natural Gas Production ⁴	Emission Intensity for Natural Gas Production ⁵		
		CO ₂	CH ₄	Total		CO ₂	CH ₄	Total		CO ₂	CH ₄	Total
		kilotonnes of eCO ₂			%	kilotonnes of eCO ₂			TJ	tonnes of eCO ₂ /GJ		
Combustion	Fossil Fuel Production	35,500	2,400	37,900	64%	22,720	1,536	24,256	6,546,148	3.471	0.235	3.705
	Pipelines	9,970	210	10,180	64%	6,381	134	6,515		0.975	0.021	0.995
Fugitive	Natural Gas	29	24,000	24,029	100%	29	24,000	24,029		0.004	3.666	3.671
	Venting	7,820	0	7,820	64%	5,005	0	5,005		0.765	0.000	0.765
	Flaring	7,380	660	8,040	64%	4,723	422	5,146		0.722	0.065	0.786
Total		60,699	27,270	87,969		38,858	26,093	64,951		6,546,148	5.936	3.986

¹Source: Environment Canada (2003) Canada's Greenhouse Gas Inventory 1990-2001

²Calculated based on Fuel Production Data from Statistics Canada Catalogue 57-300 (See Table 7-3)

³Calculated by multiplying 'Emissions from Natural Gas and RPP Production' with 'Percent Attributable to Natural Gas Production'

⁴Calculated based on Fuel Production Data from Statistics Canada Catalogue 57-300 (See Table 7-3)

⁵Calculated by dividing 'Emissions' by 'Energy Use by Natural Gas Production'

Exhibit B-2 2001 GHG Emissions Associated with the Production, Refining and Transportation of Refined Petroleum Products

Category	Sources	Emissions from RPP and Natural Gas Production			Percent Attributable to RPP Production	Emissions from RPP Production			Energy Use by RPP Production	Emission Intensity for RPP Production		
		CO2	CH4	Total		CO2	CH4	Total		CO2	CH4	Total
		kilotonnes of eCO2				%	kilotonnes of eCO2			TJ	tonnes of eCO2/GJ	
Combustion	Petroleum Refining	29,000	9	29,009	100%	29,000	9	29,009	3,741,610	7.751	0.002	7.753
	Fossil Fuel Production	35,500	2,400	37,900	36%	12,780	864	13,644		3.416	0.231	3.647
	Pipelines	9,970	210	10,180	36%	3,589	76	3,665		0.959	0.020	0.979
Fugitive	Oil	78	14,000	14,078	100%	78	14,000	14,078		0.021	3.742	3.763
	Venting	7,820	0	7,820	36%	2,815	0	2,815		0.752	0.000	0.752
	Flaring	7,380	660	8,040	36%	2,657	238	2,894		0.710	0.064	0.774
Total		60,748	17,270	78,018		50,919	15,186	66,105	3,741,610	13.609	4.059	17.668

¹Source: Environment Canada (2003) Canada's Greenhouse Gas Inventory 1990-2001

²Calculated based on Fuel Production Data from Statistics Canada Catalogue 57-300 (See Table 7-3)

³Calculated by multiplying 'Emissions from Natural Gas and RPP Production' with 'Percent Attributable to Natural Gas Production'

⁴Calculated based on Fuel Production Data from Statistics Canada Catalogue 57-300 (See Table 7-3)

⁵Calculated by dividing 'Emissions' by 'Energy Use by Natural Gas Production'

Exhibit B-3. Canadian Production of Natural Gas and Refined Petroleum Products in 2001¹

	NATURAL GAS (TJ)	REFINED PETROLEUM PRODUCTS (TJ)
PRODUCTION	7,202,051	4,451,951
EXPORTS	4,120,410	859,951
IMPORTS	148,953	454,058
DOMESTIC AVAILABILITY	3,368,727	3,907,084
CONVERTED TO:		
ELECTRICITY	334,061	19,725
REFINED PRODUCTS	19,628	
COKE AND MFG GAS		
NET DOMESTIC SUPPLY	2,992,227	3,781,500
PRODUCER CONSUMPTION	672,681	406,110
NON ENERGY APPLICATIONS	159,688	434,426
ENERGY USE FINAL DEMAND	2,159,858	2,882,036
Less Pipelines	200,051	470
Less Petroleum Refining	47,446	-
Equals NET FINAL DEMAND	1,912,361	2,881,566
TOTAL ENERGY PRODUCTION	6,546,148	3,741,610
RATIO OF TOTAL ENERGY PRODUCTION	64%	36%

¹Source: Environment Canada (2003) Canada's Greenhouse Gas Inventory 1990-2001

Exhibit B-4 Retention Rates of Various Materials

Material	Tonnes of Product Made Per Ton of Recovered Materials (i.e. Collected)
Newsprint	0.79
Fine Paper	0.61
Cardboard	0.68
Other Paper	0.61
Aluminum	0.84
Steel	0.79
Copper Wire ¹	0.82
Glass Bottles	0.71
HDPE	0.86
PET	0.86
Other Plastic	0.68
Plastics for Asphalt	0.54
CRT Glass	0.82
Lead Bullion	0.82

¹ Assumed to be an average of aluminum and steel.

² FAL (2002)

Exhibit B-5 Current Mix Values for Various Material Types

Material	% of Current Production from Recycled Inputs	% of Current Production from "Virgin" Inputs
Newsprint	19.44%	80.56%
Fine Paper	3.12%	96.88%
Cardboard	30.24%	69.76%
Other Paper	17.39%	82.61%
Aluminum	52.36%	47.64%
Steel	14.12%	85.88%
Glass	30.47%	69.53%
HDPE	14.90%	85.10%
PET	28.64%	71.36%
Other Plastic	0.92%	99.08%

Source: Enviro RIS (2000)

Exhibit B-6 Energy Use for Virgin Production of Rolled Aluminum

	Primary Energy (GJ/tonne)														Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri- cants	Petroleum (Non- specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	1.1	7.4	19.7	-	1.2	-	11.7	0.1	-	2.9	-	0.0	1.0	0.0	45.1
Bauxite Mining	0.01	-	-	-	1.0	-	0.3	0.1	-	-	-	-	-	-	1.3
Alumina Refining	0.9	7.3	17.5	-	0.1	-	11.1	-	-	0.4	-	0.04	0.9	0.0002	38.2
Anode Production	0.2	0.1	2.2	-	0.1	-	0.3	-	-	2.5	-	0.003	0.1	-	5.5 ¹
Manufacturing	58.2	-	4.3	-	0.2	0.0	1.6	0.0	-	-	-	-	-	-	64.2
Smelting	57.4	-	1.9	-	0.2	-	0.7	-	-	-	-	-	-	-	60.2
Ingot Casting	0.8	-	2.4	-	0.01	0.02	0.9	0.00	-	-	-	-	-	-	3.3
Fabrication	4.5	-	2.6	-	0.0	0.0	0.0	0.0	-	-	-	-	-	-	7.2
Rolling	4.5	-	2.6	-	0.01	0.01	0.01	0.04	-	-	-	-	-	-	7.2
Transportation	-	-	-	-	2.2	-	1.6	-	-	-	-	-	-	-	3.8
Bauxite Mining	-	-	-	-	0.2	-	0.9	-	-	-	-	-	-	-	1.1
Alumina Refining	-	-	-	-	0.2	-	0.6	-	-	-	-	-	-	-	0.8
Anode Production	-	-	-	-	0.00	-	0.02	-	-	-	-	-	-	-	0.0
Smelting	-	-	-	-	0.02	-	0.00	-	-	-	-	-	-	-	0.0
Ingot Casting	-	-	-	-	0.7	-	-	-	-	-	-	-	-	-	0.7
Rolling	-	-	-	-	1.0	-	0.02	-	-	-	-	-	-	-	1.1
TOTAL	63.8	7.4	26.7	-	3.5	0.03	14.9	0.1	-	2.9	-	0.04	1.0	0.0002	120.3

¹Other: Coke/Pitch Feedstock (19.82)

Exhibit B-7 Energy Use for Recycled Production of Rolled Aluminum

	Primary Energy (GJ/tonne)														Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.4	-	1.7	-	0.01	-	0.2	0.001	-	-	-	-	-	-	2.2
Shred and Decoat	0.4	-	1.7	-	0.01	-	0.2	0.001	-	-	-	-	-	-	2.2
Manufacturing	0.9	-	5.2	-	0.02	-	0.04	0.00	-	-	-	-	-	-	6.2
Ingot Casting	0.9	-	5.2	-	0.02	-	0.04	0.00	-	-	-	-	-	-	6.2
Fabrication	4.5	-	2.6	-	0.01	0.01	0.01	0.04	-	-	-	-	-	-	7.2
Rolling	4.5	-	2.6	-	0.01	0.01	0.01	0.04	-	-	-	-	-	-	7.2
Transportation	-	-	-	-	1.2	-	0.02	-	-	-	-	-	-	-	1.2
Shred and Decoat	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	0.01
Ingot Casting	-	-	-	-	0.1	-	-	-	-	-	-	-	-	-	0.1
Rolling	-	-	-	-	1.0	-	0.02	-	-	-	-	-	-	-	1.1
TOTAL	5.8	-	9.5	-	1.2	0.01	0.2	0.04	-	-	-	-	-	-	16.8

Exhibit B-8 Energy Use for Virgin Production of Extruded Aluminum

	Primary Energy (GJ/tonne)														Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	1.1	7.4	19.7	-	1.2	-	11.7	0.1	-	2.9	-	0.04	1.0	0.0002	45.1
Bauxite Mining	0.01	-	-	-	1.0	-	0.3	0.1	-	-	-	-	-	-	1.3
Alumina Refining	0.9	7.3	17.5	-	0.1	-	11.1	-	-	0.4	-	0.04	0.9	0.0002	38.2
Anode Production	0.2	0.1	2.2	-	0.1	-	0.3	-	-	2.5	-	0.003	0.1	-	5.5 ¹
Manufacturing	58.2	-	4.3	-	0.2	0.02	1.6	0.003	-	-	-	-	-	-	64.2
Smelting	57.4	-	1.9	-	0.2	-	0.7	-	-	-	-	-	-	-	60.2
Ingot Casting	0.8	-	2.4	-	0.01	0.02	0.9	0.003	-	-	-	-	-	-	3.3
Fabrication	0.03	0.04	11.1	-	-	-	-	-	-	0.01	-	0.001	0.02	-	11.2
Extrusion	0.03	0.04	11.1	-	-	-	-	-	-	0.01	-	0.001	0.02	-	11.2
Transportation	-	-	-	-	1.8	-	1.5	-	-	-	-	-	-	-	3.4
Bauxite Mining	-	-	-	-	0.2	-	0.9	-	-	-	-	-	-	-	1.1
Alumina Refining	-	-	-	-	0.2	-	0.6	-	-	-	-	-	-	-	0.8
Anode Production	-	-	-	-	0.0	-	0.0	-	-	-	-	-	-	-	0.0
Smelting	-	-	-	-	0.0	-	0.0	-	-	-	-	-	-	-	0.0
Ingot Casting	-	-	-	-	0.7	-	-	-	-	-	-	-	-	-	0.7
Extrusion	-	-	-	-	0.6	-	0.0	-	-	-	-	-	-	-	0.7
TOTAL	59.3	7.5	35.1	-	3.1	0.02	14.8	0.1	-	2.9	-	0.04	1.0	0.0002	123.9

¹Other: Coke/Pitch Feedstock (19.82)

Exhibit B-9 Energy Use for Recycled Production of Extruded Aluminum

	Primary Energy (GJ/tonne)														Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.4	-	1.7	-	0.01	-	0.2	0.001	-	-	-	-	-	-	2.2
Shred and Decoat	0.4	-	1.7	-	0.01	-	0.2	0.001	-	-	-	-	-	-	2.2
Manufacturing	0.9	-	5.2	-	0.02	-	0.04	0.001	-	-	-	-	-	-	6.2
Ingot Casting	0.9	-	5.2	-	0.02	-	0.04	0.001	-	-	-	-	-	-	6.2
Fabrication	5.3	-	2.7	-	0.01	0.04	0.2	0.001	-	-	-	-	-	-	8.2
Extrusion	5.3	-	2.7	-	0.01	0.04	0.2	0.001	-	-	-	-	-	-	8.2
Transportation	-	-	-	-	0.8	-	-	-	-	-	-	-	-	-	0.8
Shred and Decoat	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	0.01
Ingot Casting	-	-	-	-	0.1	-	-	-	-	-	-	-	-	-	0.1
Extrusion	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6
TOTAL	6.6	-	9.5	-	0.8	0.04	0.4	0.003	-	-	-	-	-	-	17.4

Exhibit B-10 Energy Use for Virgin Production of Shape Cast Aluminum

	Primary Energy (GJ/tonne)														Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	1.1	7.4	19.7	-	1.2	-	11.7	0.1	-	2.9	-	0.04	1.0	0.0002	45.1
Bauxite Mining	0.01	-	-	-	1.0	-	0.3	0.1	-	-	-	-	-	-	1.3
Alumina Refining	0.9	7.3	17.5	-	0.1	-	11.1	-	-	0.4	-	0.04	0.9	0.0002	38.2
Anode Production	0.2	0.1	2.2	-	0.1	-	0.3	-	-	2.5	-	0.003	0.1	-	5.5 ¹
Manufacturing	58.2	-	4.3	-	0.2	0.02	1.6	0.003	-	-	-	-	-	-	64.2
Smelting	57.4	-	1.9	-	0.2	-	0.7	-	-	-	-	-	-	-	60.2
Ingot Casting	0.8	-	2.4	-	0.01	0.02	0.9	0.003	-	-	-	-	-	-	3.3
Fabrication	0.03	0.04	11.1	-	-	-	-	-	-	0.01	-	0.001	0.02	-	11.2
Shape Casting	0.03	0.04	11.1	-	-	-	-	-	-	0.01	-	0.001	0.02	-	11.2
Transportation	-	-	-	-	1.8	-	1.5	-	-	-	-	-	-	-	3.4
Bauxite Mining	-	-	-	-	0.2	-	0.9	-	-	-	-	-	-	-	1.1
Alumina Refining	-	-	-	-	0.2	-	0.6	-	-	-	-	-	-	-	0.8
Anode Production	-	-	-	-	0.0	-	0.0	-	-	-	-	-	-	-	0.0
Smelting	-	-	-	-	0.0	-	0.0	-	-	-	-	-	-	-	0.0
Ingot Casting	-	-	-	-	0.7	-	-	-	-	-	-	-	-	-	0.7
Shape Casting	-	-	-	-	0.6	-	0.0	-	-	-	-	-	-	-	0.7
TOTAL	59.3	7.5	35.1	-	3.1	0.02	14.8	0.1	-	2.9	-	0.04	1.0	0.0002	123.9

¹Other: Coke/Pitch Feedstock (19.82)

Exhibit B-11 Energy Use for Recycled Production of Shape Cast Aluminum

	Primary Energy (GJ/tonne)														Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.4	-	1.7	-	0.01	-	0.2	0.001	-	-	-	-	-	-	2.2
Shred and Decoat	0.4	-	1.7	-	0.01	-	0.2	0.001	-	-	-	-	-	-	2.2
Manufacturing	0.9	-	5.2	-	0.02	-	0.04	0.001	-	-	-	-	-	-	6.2
Ingot Casting	0.9	-	5.2	-	0.02	-	0.04	0.001	-	-	-	-	-	-	6.2
Fabrication	0.03	0.04	11.1	-	-	-	-	-	-	0.01	-	0.001	0.02	-	11.2
Shape Casting	0.03	0.04	11.1	-	-	-	-	-	-	0.01	-	0.001	0.02	-	11.2
Transportation	-	-	-	-	0.8	-	0.02	-	-	-	-	-	-	-	0.8
Shred and Decoat	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	0.0
Ingot Casting	-	-	-	-	0.1	-	-	-	-	-	-	-	-	-	0.1
Shape Casting	-	-	-	-	0.6	-	0.02	-	-	-	-	-	-	-	0.7
TOTAL	1.3	0.0	18.0	-	0.8	-	0.2	0.002	-	0.01	-	0.001	0.02	-	20.4

Exhibit B-12 PFC-Anode Information

Gas	Total 2001 Emissions ¹ (kilotonnes eCO ₂)	Total 2001 Primary Aluminum Production ² (kilotonnes)	Estimated Emission Factor (kilotonnes eCO ₂ / kilotonne of Al)
PFCs	4,160	2,583	1.61
CO ₂	6,000		2.32

¹Environment Canada, 2002. 2001 Greenhouse Gas Emissions Inventory Summary for Canada.

²CIEEDAC, 2003. A Review of Energy Consumption and Related Data: Canadian Aluminum Industries 1990-2001

Exhibit B-13 Energy Use for Virgin Production of Steel

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.7	-	0.7	0.8	-	-	0.003	-	-	-	-	-	-	2.2
Manufacturing	0.4	15.6	5.5	-	-	-	-	-	1.1	-	-	-	-	22.7
Transportation	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6
TOTAL	1.1	15.6	6.2	1.4	-	-	0.003	-	1.1	-	-	-	-	25.5

Exhibit B-14 Energy Use for Recycled Production of Steel

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	3.7	-	5.5	-	-	-	-	-	0.1	-	-	-	-	9.3
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	3.67	-	5.5	0.4	-	-	-	-	0.1	-	-	-	-	9.7

Exhibit B-15 Derivation of Energy per Tonne Estimates for Steel Raw Materials Acquisition.

Extraction	Energy Use (KJ) for 1 sq meter of 30 gauge steel cladding = 3.8 kg steel ¹	Energy Use (KJ) per kg steel	Energy Use (KJ) per tonne steel	Energy Use (GJ) per tonne steel
Diesel	2,945	775	775,000	0.78
Gasoline	12	3	3,158	0.003
Delivered Electricity	2,779	731	731,316	0.73
Natural Gas	2,663	701	700,789	0.70

¹Athena Institute (1998)

Exhibit B-16 Energy Use at Materials Recovery Facility

(a) kgs e CO2 per tonne of recycled content at MRF*	(b) kg eCO2/kWh Electricity Input	(c) kwh per ton of recycled content (=a/b)	(d) GJ per delivered kwh	(e) GJ electricity per tonne of product at MRF (=c x d)
0.6	0.29	2.1	0.004	0.008

¹Torrie Smith Associates. Greenhouse Gas Emissions from Waste Management: Implications to Modelling. September 2003. Note: Uses data for "waste management facilities" as surrogate for MRFs.

Exhibit B-17 Manufacturing Energy Use for Selected Materials, Virgin Inputs

Product	Energy (GJ/tonne)	Fuel breakdown (in percent)														
		Delivered Electricity	Coal	Natural Gas	Nat Gas feedstock (other fuels)	Oils feedstock	Diesel	LPG	Light Fuel	Residual Fuel	Gasoline	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other
Aluminum	64.19	90.6%	0.0%	6.7%	0.0%	0.0%	0.3%	0.0%	0.0%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Steel	22.67	1.8%	69.0%	24.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.9%	0.0%	0.0%	0.0%	0.0%
Copper Wire	67.87	32.7%	4.7%	61.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.6%	0.1%
Glass	6.00	5.0%	0.0%	85.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	0.0%	0.0%	0.0%	0.0%
HDPE	33.25	17.4%	0.0%	50.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	32.1%	0.0%	0.0%	0.0%	0.0%
PET	62.21	14.4%	0.0%	58.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26.9%	0.0%	0.0%	0.0%	0.0%
Other Plastic	35.25	7.7%	0.0%	70.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	22.0%	0.0%	0.0%	0.0%	0.0%
Tires	102.53	43.8%	0.0%	41.9%	0.0%	0.0%	0.0%	0.0%	0.0%	13.1%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%
Newsprint	14.11	50.9%	0.0%	37.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	1.6%	0.0%	0.0%	0.0%
Fine Paper	35.23	10.9%	0.0%	32.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	46.7%	0.0%	0.0%	0.0%
Cardboard	30.93	11.3%	0.0%	31.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	46.8%	0.0%	0.0%	0.0%
Other Paper	32.56	11.7%	0.0%	32.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	46.3%	0.0%	0.0%	0.0%

Exhibit B-18 Manufacturing Energy for Selected Materials, from Recycled Inputs

Product	Energy (GJ/tonne)	Fuel breakdown														
		Delivered Electricity	Coal	Natural Gas	Nat Gas feedstock (other fuels)	Oils feedstock	Diesel	LPG	Light Fuel	Residual Fuel	Gasoline	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other
Aluminum	6.18	14.8%	0.0%	84.2%	0.0%	0.0%	0.3%	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Steel	9.30	39.4%	0.0%	59.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%	0.0%	0.0%	0.0%	0.0%
Copper Wire	6.00	13.2%	0.0%	58.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26.1%	0.0%	0.0%	0.0%	2.5%
Glass	4.20	5.0%	0.0%	90.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.0%	0.0%	0.0%	0.0%	0.0%
HDPE	6.00	75.0%	0.0%	16.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.9%	0.0%	0.0%	0.0%	0.0%
PET	6.00	75.0%	0.0%	16.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.9%	0.0%	0.0%	0.0%	0.0%
Other Plastic	6.00	75.0%	0.0%	16.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.9%	0.0%	0.0%	0.0%	0.0%
Tires	42.11	43.8%	0.0%	41.9%	0.0%	0.0%	0.0%	0.0%	0.0%	13.1%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%
Newsprint	8.35	23.4%	0.0%	56.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%
Fine Paper	13.09	30.0%	0.0%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%
Cardboard	12.78	21.4%	0.0%	58.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%
Other Paper	10.30	24.7%	0.0%	55.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%

Exhibit B-19 Transportation Energy Use – Virgin

Total GJ per tonne	Total GJ per Tonne -- Truck (Diesel)
Raw Materials Acquisition ¹	0.2
Manufacturing and Fabrication	0.07
Transport to Consumer	0.30
Total	0.58

¹Athena Institute. A Life Cycle Analysis of Solid Wood and Steel Cladding, September 1998

Note: Used as surrogate for other materials.

Exhibit B-20 Transportation Energy Use - Recycled

Total GJ per tonne	Total GJ per Tonne -- Truck (Diesel)
Raw Materials Acquisition	N/A
Manufacturing and Fabrication	0.07
Transport to Consumer	0.30
Total	0.38

Exhibit B-21 Transportation Associated with Manufacturing and Fabrication

(a) Assumed total kilometers traveled	(b) Total tonnes per trip ¹	(c) Total tonne-km (=a/b)	(d) Litres per km ²	(e) Litres per tonne (=a*d/b)	(f) GJ/litre ³	(g) GJ per tonne
100	22.68	4.41	0.45	1.96	0.04	0.07

¹Assumes 25 short tons per trip.

²Assumes 5.3 miles per gallon, or 2.3 km per litre.

³Source: http://bioenergy.ornl.gov/papers/misc/energy_conv.html

Exhibit B-22 Transport to Consumer -- Glass (used as surrogate for other materials)

(a) Assumed total kilometers traveled ¹	(b) Total tonnes per trip ²	(c) Total tonne-km (=a/b)	(d) Litres per km ^{2 3}	(e) Litres per tonne (=a*d/b)	(f) GJ/litre ⁴	(g) GJ per tonne
426	22.68	18.78	0.45	8.36	0.04	0.30

¹Athena Institute (1998)

²Assumes 25 short tons per trip.

³Assumes 5.3 miles per gallon, or 2.3 km per litre.

⁴Source: http://bioenergy.ornl.gov/papers/misc/energy_conv.html

Exhibit B-23 Energy Use for Virgin Production of Copper Wire

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	15.4	-	8.7	0.4	-	1.1	-	-	-	-	25.7
Manufacturing	22.2	3.2	41.9	-	0.02	-	-	-	1.1	-	-	0.4	0.1	67.9
Transportation	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6
TOTAL	22.2	3.2	41.9	16.0	0.02	8.7	0.4	-	1.1	-	-	0.4	0.4	94.1

Exhibit B-24 Energy Use for Recycled Production of Copper Wire

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	0.8	-	3.5	-	-	-	-	-	1.6	-	-	-	-	6.0
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	0.8	-	3.5	0.4	-	-	-	-	1.6	-	-	-	-	6.4

Exhibit B-25 Energy Use for Virgin Production of Glass Bottles

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.1	-	0.2	-	0.01	-	-	-	0.3	-	-	-	-	0.6
Manufacturing	0.3	-	5.1	-	-	-	-	-	0.6	-	-	-	-	6.0
Transportation	-	-	-	0.2	-	-	-	-	-	-	-	-	-	0.2 ¹
TOTAL	0.4	-	5.3	0.2	0.01	-	-	-	0.9	-	-	-	-	6.8

¹ Includes transportation associated with raw materials acquisition and transportation. "Other" fuel = heavy fuel oil for marine transport.

Exhibit B-26 Energy Use for Recycled Production of Glass Bottles

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	0.2	-	3.8	-	-	-	-	-	0.2	-	-	-	-	4.2
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	0.2	-	3.8	0.4	-	-	-	-	0.2	-	-	-	-	4.6

Exhibit B-27 Derivation of Per-Tonne Energy Estimates for Raw Materials Acquisition of Glass¹

Fuel	(a) Energy Use in 2001, PJ	(b) Mega-tonnes of "Other Non-Metal Mines" Produced in 2001	(c) PJ Energy/ Megatonne (=a/b)	(d) GJ/Tonne
Electricity	1.5	16.22	0.1	0.09
Natural Gas	2.9		0.2	0.18
Light Fuel Oil, Diesel Fuel Oil and Kerosene	3.7		0.2	0.23
Heavy Fuel Oil	0.8		0.0	0.05
Still Gas and Petroleum Coke	0.0		0.0	0.00
LPG and Gas Plant NGL	0.2		0.0	0.01
Coal, Coke and Coke Oven Gas	0.0		0.0	0.00
Wood Waste and Pulping Liquor	0.0		0.0	0.00
Other ²	0.0		0.0	0.00

¹Source: Natural Resources Canada. Comprehensive Energy Use Database. Table 15. http://oee.nrcan.gc.ca/Neud/dpa/trends_id_ca.cfm.

²"Other" includes steam and waste fuels.

Exhibit B-28 Energy Use for Virgin Production of HDPE

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)	Total Energy (exc feedstocks)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Nat Gas Feedstock (other fuels)	Oils Feedstock	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other		
Raw Materials Acquisition	-	-	-	22.7	25.0	-	-	-	-	-	-	-	-	-	-	47.7	-
Manufacturing	5.8	-	33.3	-	-	-	-	-	-	-	10.7	-	-	-	-	33.3	33.3
Transportation	-	-	0.6	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6	0.6
TOTAL	5.8	-	33.8	22.7	25.0	0.6	-	-	-	-	10.7	-	-	-	-	81.6	33.8

Exhibit B-29 Energy Use for Recycled Production of HDPE

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	4.5	-	1.0	-	-	-	-	-	0.5	-	-	-	-	6.0
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	4.5	-	1.0	0.4	-	-	-	-	0.5	-	-	-	-	6.4

Exhibit B-30 Energy Use for Virgin Production of PET

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)	Total Energy (exc feedstocks)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Nat Gas Feedstock (other fuels)	Oils Feeds tock	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri- cants	Petroleum (Non- specified)	Biomass	Hydro	Nuclear	Other		
Raw Materials Acquisition	-	-	-	13.8	7.8	-	-	-	-	-	-	-	-	-	21.6	43.2	7.8
Manufacturing	9.0	-	36.5	-	-	-	-	-	-	-	16.7	-	-	-	-	62.2	25.7
Transportation	-	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6	0.6
TOTAL	9.0	-	36.5	13.8	7.8	0.6	-	-	-	-	16.7	-	-	-	21.6	106.0	34.1

Exhibit B-31 Energy Use for Recycled Production of PET

	Primary Energy (GJ/tonne)														Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri- cants	Petroleum (Non- specified)	Biomass	Hydro	Nuclear	Other		
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	4.5	-	1.0	-	-	-	-	-	0.5	-	-	-	-	-	6.0
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	-	0.4
TOTAL	4.5	-	1.0	0.4	-	-	-	-	0.5	-	-	-	-	-	6.4

Exhibit B-32 Energy Use for Virgin Production of Other Plastic (LDPE)

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)	Total Energy (exc feedstocks)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Nat Gas Feedstock (other fuels)	Oils Feedstock	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other		
Raw Materials Acquisition	-	-	-	33.4	14.3	-	-	-	-	-	-	-	-	-	-	47.7	-
Manufacturing	2.7	-	24.8	-	-	-	-	-	-	-	7.8	-	-	-	-	35.3	35.3
Transportation	-	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6	0.6
TOTAL	2.7	-	24.8	33.4	14.3	0.6	-	-	-	-	7.8	-	-	-	-	83.6	35.8

Exhibit B-33 Energy Use for Recycled Production of Other Plastic (LDPE)

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	4.5	-	1.0	-	-	-	-	-	0.5	-	-	-	-	6.0
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	4.5	-	1.0	0.4	-	-	-	-	0.5	-	-	-	-	6.4

Exhibit B-34 High Density Polyethylene

Fuel	Process Energy Intensity (GJ/tonne)	Percentage of Total Fuel Consumption	Feedstock Energy Intensity (GJ/tonne)	Total
Electricity	5.79	17.4%	0	5.79
Oil	10.67	32.1%	25.01	35.68
Other Fuels	16.79	50.5%	22.72	39.51
Total	33.25	100.0%	47.73	80.98

Source: Fred Edgecombe, personal communication to Torrie Smith, March 2001.

Exhibit B-35 PET Bottle Grade

Fuel	Process Energy Intensity (GJ/tonne)	Percentage of Total Fuel Consumption	Feedstock Energy Intensity (GJ/tonne)	Total
Electricity	5.79	17.41%	0	5.79
Oil	10.67	32.09%	25.01	35.68
Other Fuels	16.79	50.50%	22.72	39.51
Total	33.25	100%	47.73	80.98

Source: Fred Edgecombe, personal communication to Torrie Smith, March 2001.

Exhibit B-36 Linear Low Density Polyethylene (Other Plastics)

Fuel	Process Energy Intensity (GJ/tonne)	Percentage of Total Fuel Consumption	Feedstock Energy Intensity (GJ/tonne)	Total
Electricity	2.71	7.69%	0	2.71
Oil	7.77	22.04%	14.32	22.09
Other Fuels	24.77	70.27%	33.41	58.18
Total	35.25	100.00%	47.33	82.98

Source: Fred Edgecombe, personal communication to Torrie Smith, March 2001.

Exhibit B-37 Energy Use for Virgin Production of Tires

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Manufacturing	44.9	-	43.0	-	-	13.5	-	-	-	-	-	-	1.2	102.6
Transportation	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6
TOTAL	44.9	-	43.0	0.6	-	13.5	-	-	-	-	-	-	1.2	103.1

Exhibit B-38 Energy Use for Recycled Production of Tires

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	18.4	-	17.7	-	-	5.5	-	-	-	-	-	-	0.5	42.1
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	18.4	-	17.7	0.4	-	5.5	-	-	-	-	-	-	0.5	42.5

Exhibit B-39 Energy Use for Virgin Production of Newsprint

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Light Fuel	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	0.002	0.9	-	0.02	0.04	-	-	-	-	-	-	-	1.0
Manufacturing	7.2	-	5.3	-	-	-	-	-	-	-	1.4	0.2	-	-	-	14.1
Transportation	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	-	0.6
TOTAL	7.2	-	5.3	0.002	1.5	-	0.02	0.04	-	-	1.4	0.2	-	-	-	15.6

Exhibit B-40 Energy Use for Recycled Production of Newsprint

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	2.0	-	4.7	-	-	-	-	-	1.7	-	-	-	-	8.4
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4 ¹
TOTAL	2.0	-	4.7	0.4	-	-	-	-	1.7	-	-	-	-	8.7

¹"Other" fuels includes steam and waste fuels.

Exhibit B-41 Energy Use for Virgin Production of Fine Paper

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Light Fuel	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	0.002	0.9	-	0.02	0.04	-	-	-	-	-	-	-	1.0
Manufacturing	3.8	-	11.4	-	-	-	-	-	-	-	3.5	16.5	-	-	-	35.2
Transportation	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	-	0.6
TOTAL	3.8	-	11.4	0.002	1.5	-	0.02	0.04	-	-	3.5	16.5	-	-	-	36.8

Exhibit B-42 Energy Use for Recycled Production of Fine Paper

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	3.9	-	6.6	-	-	-	-	-	2.6	-	-	-	-	13.1
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	3.9	-	6.6	0.4	-	-	-	-	2.6	-	-	-	-	13.5

Exhibit B-43 Energy Use for Virgin Production of Cardboard

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Light Fuel	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	0.002	0.9	-	0.02	0.04	-	-	-	-	-	-	-	1.0
Manufacturing	3.5	-	9.9	-	-	-	-	-	-	-	3.1	14.5	-	-	-	30.9
Transportation	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	-	0.6
TOTAL	3.5	-	9.9	0.002	1.5	-	0.02	0.04	-	-	3.1	14.5	-	-	-	32.5

Exhibit B-44 Energy Use for Recycled Production of Cardboard

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	2.7	-	7.5	-	-	-	2.6	-	-	-	-	-	-	12.8
Transportation	-	-	-	-	-	-	-	-	-	-	-	-	-	0.4
TOTAL	2.7	-	7.5	-	-	-	2.6	-	-	-	-	-	-	26.02

Exhibit B-45 Energy Use for Virgin Production of “Other” Paper

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Light Fuel	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	0.002	0.9	-	0.02	0.04	-	-	-	-	-	-	-	1.0
Manufacturing	3.8	-	10.4	-	-	-	-	-	-	-	3.3	15.1	-	-	-	32.6
Transportation	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	-	0.6
TOTAL	3.8	-	10.4	0.002	1.5	-	0.02	0.04	-	-	3.3	15.1	-	-	-	34.1

Exhibit B-46 Energy Use for Recycled Production of “Other” Paper

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Manufacturing	2.5	-	5.7	-	-	-	-	-	2.1	-	-	-	-	10.3
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	2.5	-	5.7	0.4	-	-	-	-	2.1	-	-	-	-	10.7

Exhibit B-47 Energy Use for Virgin Production of Tissue Paper

	Primary Energy (GJ/tonne)															Total Energy (inc electricity)
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Kerosene & Stove Oil	Diesel	LPG	Light Fuel	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	-	-	-	1.67	6.58	1.1	-	-	-	-	-	-	9.4
Manufacturing	2.9	6.0	4.7	-	-	-	-	-	-	-	-	20.4	-	-	-	34.0
Transportation	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	-	0.6
TOTAL	2.9	6.0	4.7	-	0.6	-	1.67	6.58	1.1	-	-	20.4	-	-	-	43.9

Exhibit B-48 Energy Use for Recycled Production of Tissue Paper

	Primary Energy (GJ/tonne)												Total Energy (inc electricity)	
	Delivered Electricity (GJ/tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/Lubricants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear		Other
Raw Materials Acquisition	0.01	-	-	-	-	3.4	-	-	-	-	-	-	-	3.36
Manufacturing	3.8	-	6.0	-	-	-	-	-	3.6	-	-	-	-	13.5
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	3.8	-	6.0	0.4	-	3.4	-	-	3.6	-	-	-	-	17.2

Exhibit B-49 Derivation of Per-Tonne Energy Estimates for Raw Material Acquisition of Paper

Input	Calculation	Units	Primary Energy					
			Kerosene & Stove Oil	Diesel	Light Fuel Oil	Heavy Fuel Oil	Total	
a	Fuel Consumption for Harvesting ¹	megalitres	0.9	446.6	12.2	15.9	475.6	
b	Energy Content ²	GJ / megalitre	37,680	38,300	38,800	42,500	157,280	
c	Fuel Consumption for Harvesting	(= a * b)	GJ	33,912	17,104,780	473,360	675,750	18,287,802
d	% of Fuel Consumption for Harvesting Pulpwood ³	%	50%					
e	Fuel Consumption for Harvesting Pulpwood	(= c * d)	GJ	16,956	8,552,390	236,680	337,875	9,143,901
f	Production of pulpwood ⁴	tonnes	9,570,000					
g	Energy Intensity of Harvesting Pulpwood	(= e / f)	GJ / tonne	0.00177	0.89367	0.02473	0.03531	0.95548

¹Source: Statistics Canada, CANSIM, Table 128-0003, 2001 Annual Data

²Ibid.

³The percentage is based on best judgment

⁴Source: NRCan Web Site, Office of Energy Efficiency, Comprehensive Energy Use Database, Accessed on Mar 9, 2004, http://oee.nrcan.gc.ca/Neud/dpa/trends_id_ca.cfm

Exhibit B-50 Waste Management Emissions

Waste Management Process	Emission Factor (kgs eCO ₂ per tonne of waste)
Waste Collection and Transportation	10
Landfill Heavy Equipment	4
Energy Use at Waste Management Facilities	0.6
Total	14.6

Source: Ralph Torrie. Greenhouse Gas Emissions from Waste Management: Implications to Modelling. September 2003.

Exhibit B-51 Energy Use for Virgin Production of Asphalt

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	-	-	0.1	0.01	-	0.03	-	-	-	-	0.1
Manufacturing	0.04	-	0.3	-	-	-	-	-	-	-	-	-	-	0.4
Transportation	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6
TOTAL	0.04	-	0.3	0.6	-	0.1	0.01	-	0.03	-	-	-	-	1.1

Exhibit B-52 Energy Use for Recycled Production of Asphalt Using Recycled Plastic

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	0.1	0.01	-	0.1	-	-	-	-	0.17
Manufacturing	2.4	0.1	0.6	-	0.01	-	-	-	-	-	-	0.02	-	3.1
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	2.4	0.1	0.6	0.4	0.01	0.1	0.01	-	0.1	-	-	0.02	-	3.6

Exhibit B-53 Energy Use for Virgin Production of CRT Glass

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	-	-	0.73	0.04	-	0.74	-	-	-	-	1.52
Manufacturing	0.65	0.24	6.77	-	-	-	-	-	-	-	-	0.03	0.00	7.69
Transportation	-	-	-	0.58	-	-	-	-	-	-	-	-	-	0.58
TOTAL	0.65	0.24	6.77	0.58	-	0.73	0.04	-	0.74	-	-	0.03	0.00	9.79

Exhibit B-54 Energy Use for Recycled Production of CRT Glass

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	0.6	0.0	-	0.5	-	-	-	-	1.14
Manufacturing	1.5	0.1	4.7	-	0.00	-	-	-	-	-	-	0.02	-	6.3
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	1.5	0.1	4.7	0.4	0.0	0.6	0.0	-	0.5	-	-	0.02	-	7.8

Exhibit B-55 Energy Use for Virgin Production of Lead Bullion

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	-	-	-	-	-	0.2	0.0	-	0.17	-	-	-	-	0.4
Manufacturing	6.08	0.21	2.4	-	-	-	-	-	-	0.01	-	0.1	0.0	8.8
Transportation	-	-	-	0.6	-	-	-	-	-	-	-	-	-	0.6
TOTAL	6.1	0.2	2.4	0.6	-	0.2	0.0	-	0.2	0.0	-	0.1	0.0	9.8

Exhibit B-56 Energy Use for Recycled Production of Lead Bullion

	Primary Energy (GJ/tonne)													Total Energy (inc electricity)
	Delivered Electricity (GJ/ tonne)	Coal	Natural Gas	Diesel	LPG	Residual Fuel	Gasoline	Oil/ Lubri-cants	Petroleum (Non-specified)	Biomass	Hydro	Nuclear	Other	
Raw Materials Acquisition	0.01	-	-	-	-	0.2	0.0	-	0.2	-	-	-	-	0.42
Manufacturing	6.8	0.2	2.3	-	0.00	-	-	-	-	0.01	-	0.08	0.01	9.4
Transportation	-	-	-	0.4	-	-	-	-	-	-	-	-	-	0.4
TOTAL	6.8	0.2	2.3	0.4	0.0	0.2	0.0	-	0.2	0.0	-	0.1	0.0	10.2