LIFE CYCLE IMPACTS FOR POSTCONSUMER RECYCLED RESINS: PET, HDPE, AND PP

SUBMITTED TO:

The Association of Plastic Recyclers

SUBMITTED BY:

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Eastern Research Group (ERG)**

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TERMS AND DEFINITIONS (ALPHABETICAL)

Acidification Potential— potential of emissions such as sulfur dioxide and nitrogen oxides to result in acid rain, with damaging effects on ecosystems and buildings.

Allocation—partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Characterization Factor—factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator.

Combustion Energy—the higher heat value directly released when coal, fuel oil, natural gas, or biomass is burned for energy consumption.

Co-product—any of two or more products coming from the same unit process or product system.

Cradle-to-Gate—refers to an LCA or LCI covering life cycle stages from raw material extraction through raw material production (i.e. does not cover entire life cycle of a product system).

Cradle-to-Grave—an LCA or LCI covering all life cycle stages of a product system from raw material extraction through end-of-life and recycling when applicable.

End-of-Life—refers to the life cycle stage of a product following disposal.

Energy Demand—energy requirements of a process/product, including energy from renewable and non-renewable resources). In this study, energy demand is measured by the higher heating value of the fuel at point of extraction.

Energy of Material Resource—the energy value of fuel resources withdrawn from the planet's finite fossil reserves and used as material inputs. Some of this energy remains embodied in the material and can potentially be recovered. Alternative terms used by other LCA practitioners include "Feedstock Energy" and "Inherent Energy."

Eutrophication Potential—assesses the potential of nutrient releases to the environment to decrease oxygen content in bodies of water, which can lead to detrimental effects such as algal blooms and fish kills.

Expended Energy—energy that has been consumed (e.g., through combustion) and is no longer recoverable

Fossil Fuel—fuels with high carbon content from natural processes (e.g. decomposition of buried dead organisms) that are created over a geological time frame (e.g. millions of years). Natural gas, petroleum and coal are examples of fossil fuels.

Fugitive Emissions—unintended leaks of substances that escape to the environment without treatment. These are typically from the processing, transmission, and/or transportation of fossil fuels, but may also include leaks and spills from reaction vessels, other chemical processes, methane emissions escaping untreated from landfills, etc.

Functional Unit—quantified performance of a product system for use as a reference unit.

Global Warming Potential—an index, describing the radiative characteristics of well-mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide.[1]

Greenhouse Gas—gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide, nitrous oxide, methane, and ozone are the primary greenhouse gases in the Earth's atmosphere.

Impact Category—class representing environmental issues of concern to which life cycle inventory analysis results may be assigned.

Life Cycle—consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life Cycle Assessment—compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life Cycle Inventory—phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact Assessment—phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation—phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Non-Renewable Energy—energy from resources that cannot be created on scale to sustain consumption (i.e. cannot re-generate on human time-scale). Fossil fuels (e.g. coal, petroleum, natural gas) and nuclear power (uranium) are considered non-renewable energy resources.

Postconsumer Waste—waste resulting directly from consumer disposal of the product system of the analysis.

Process Waste—wastes from processes along the entire life cycle of the product system. Does not include postconsumer waste.

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[1] Definition from the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report - Climate Change 2001.

Precombustion Energy—the energy required for the production and processing of energy fuels, such as coal, fuel oil, natural gas, or uranium, starting with their extraction from the ground, up to the point of delivery to the customer.

Renewable Energy—energy from natural resources that can be replenished (e.g. biomass) or are not depleted by use (e.g., hydropower, sunlight, wind).

Smog Formation Potential— potential of emissions to form ground-level ozone which can affect human health and ecosystems.

Solid Waste—any wastes resulting from fuel extraction and combustion, processing, or postconsumer disposal. Solid waste in this study is measured as waste to a specific fate (e.g. landfill, incinerator).

System Boundary—set of criteria specifying which unit processes are part of a product system.

Transportation Energy—energy used to move materials or goods from one location to another throughout the various stages of a product's life cycle

Unit Process—smallest element considered in the life cycle inventory analysis for which input and output data are quantified.

Water Consumption—consumptive use of water includes freshwater that is withdrawn from a water source or watershed and not returned to that source. Consumptive water use includes water consumed in chemical reactions, water that is incorporated into a product or waste stream, water that becomes evaporative loss, and water that is discharged to a different watershed or water body than the one from which it was withdrawn.

CHAPTER 1. LIFE CYCLE METHODOLOGY

1.1. OVERVIEW

This analysis is an update and expansion of a recycled resin study completed in 2011[2] that quantified the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of recycled PET and HDPE resin from postconsumer plastic.

This study provides updated data on production of recycled PET and HDPE resin and adds new data for recycling of postconsumer polypropylene (PP) resin. In addition to updating results categories addressed in the original analysis, this report includes life cycle impact assessment (LCIA) results for additional results categories including acidification potential, eutrophication potential, and smog formation potential.

The following sections of this chapter describe key aspects of life cycle assessment methodology as applied in this analysis.

1.2. METHODOLOGY

This analysis has been conducted following internationally accepted standards for LCI and LCA methodology as outlined in the ISO 14040 and 14044 standard documents[3].

A full "cradle-to-grave" life cycle assessment (LCA) examines the sequence of steps in the life cycle of a product system, beginning with raw material extraction and continuing through material production, product fabrication, use, reuse or recycling where applicable, and final disposition. This analysis of recycled resins is a "cradle-to-gate" analysis that ends at material production. The cradle-to-gate life cycle inventory (LCI) and life cycle impact assessment (LCIA) results presented in this study quantify the total energy requirements, energy sources, water consumption, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of recycled resins. The resin data can be linked with fabrication, use, and end-of-life data to create full life cycle inventories for a variety of plastic products using recycled resin content, such as packaging or durable products.

An LCA consists of four phases:

- Goal and scope definition

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[2] Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumer Containers and Packaging. January 2011. Conducted by Franklin Associates, a Division of ERG for ACC Plastics Division, APR, NAPCOR, and PETRA. Available at https://plastics.americanchemistry.com/Education-Resources/Publications/Life-Cycle-Inventory-of-Postconsumer-HDPE-and-PET-Recycled-Resin.pdf

[3] International Standards Organization. ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

- Life cycle inventory (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation of results

The LCI phase identifies and quantifies the material inputs, energy consumption, water consumption, and environmental emissions (atmospheric emissions, waterborne wastes, and solid wastes) over the defined scope of the study. In the LCIA phase, the inventory of emissions is classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance. The results presented in this study include both inventory results and impact assessment results. Results for recycled resin are broken out by several life cycle stages to analyze the contributions of the different processes required to collect, sort, and process recycled resins.

The remainder of this chapter addresses Goal and Scope issues. Life cycle inventory data sets developed for this study are presented in Chapter 2, and LCI and LCIA results are presented in Chapter 3.

1.3. GOAL AND SCOPE

The goal of this study was to develop updated environmental data on the production of three postconsumer recycled resins: recycled PET, recycled HDPE, and recycled PP.

For a more comprehensive understanding of the environmental benefits and tradeoffs for recycled resins compared to virgin resins, this updated analysis of recycled resin production includes results for an expanded set of environmental indicators:

- Energy Consumption
- Water Consumption
- Solid Waste
- Global Warming Potential
- Acidification Potential
- Eutrophication Potential
- Smog Formation Potential

The geographic scope of this study is for recycled resin produced and sold in North America. Recycled resin results are compared with results for corresponding virgin resin produced in North America.

This analysis was conducted to provide APR, its members, and the life cycle community with transparent, detailed data and results for recycled resin. The information in this report serves several important purposes:

1. To provide stakeholders with updated data on the processes involved in collecting, sorting, and reprocessing postconsumer resins into a form ready for use in another product system.

2. To provide stakeholders with information about the relative environmental impacts of recycled and virgin plastic resins.
3. To provide data sets that can be used by any life cycle practitioner to model systems using postconsumer recycled HDPE, PET, or PP.

The remaining sections of this chapter address scoping aspects including the functional unit, product systems studied, system boundaries, data requirements, data sources, co-product allocation, recycling methodology, and impact assessment methodology.

1.3.1. Functional Unit

The function of resin is as a raw material for manufacturing a wide variety of products. Since material inputs for a product are typically specified on a mass basis, a mass of resin ready for converting is used as the functional unit. Results in Chapter 3 are shown both on a metric unit output basis (1 kg) and a US unit basis (1,000 lb).

1.3.2. Product Systems Studied

The focus of this analysis is on production of the following postconsumer recycled resins:

- HDPE
- PET
- PP

Results for postconsumer recycled resins are compared to results for corresponding virgin resins modeled using data from the ACC Plastics resins report.[4]

1.3.3. System Boundary

The recycled resin analysis begins with collection of postconsumer plastic resins and includes sorting and separation processes as well as reclaimer processing. Transportation between process steps is included.

The following are not included in this study:

Product Manufacturing. The focus of this study is production of recycled resins that can be used in a variety of product systems; therefore, converting of resins into any specific product(s) is excluded from the analysis.

Capital Equipment, Facilities, and Infrastructure. The energy and wastes associated with the manufacture of buildings, roads, pipelines, motor vehicles, industrial machinery, etc. are not included. The energy and emissions associated with production of capital

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[4] Cradle-to-Gate Life Cycle Assessment of Nine Plastic Resins and Four Polyurethane Precursors. August 2011. Conducted by Franklin Associates, a Division of ERG for ACC Plastics Division. Available at https://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-Rpt-Only/

equipment, facilities, and infrastructure generally become negligible when averaged over the total output of product or service provided over their useful lifetimes.

Support Personnel Requirements. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study, as energy requirements and related emissions are assumed to be quite small for support personnel activities.

1.3.4. Data Requirements

ISO 14044:2006 lists a number of data quality requirements that should be addressed for studies intended for public use. The data quality goals for this analysis were to use data that are (1) geographically representative for the recycled resins studied based on the locations where material sourcing and production take place, and (2) representative of current industry practices in these regions. To develop current representative data for postconsumer resin recycling, data collection forms were sent to all PET, HDPE, and PP reclaimer members of APR. Responses were received from seven PET reclaimer facilities, six facilities processing HDPE, and three PP reclaimers. The data sets were used to compile a weighted average for each resin based on each facility's recycled resin output as a percentage of the total output of that recycled resin for all reporting facilities.

The background data sets used to model energy, chemicals, etc. used by the reclaiwere drawn primarily from the US LCI database. In some cases, such as modeling of certain chemicals reported by reclaimers, the data were supplemented with data from the ecoinvent database and ERG's private North American database. The data sets used were the most current and most geographically and technologically relevant data sets available during the data collection and modeling phase of the project.

Consistency, Completeness, Precision: Data evaluation procedures and criteria were applied consistently to all primary data provided by the resin reclaimers. All primary data obtained specifically for this study were considered the most representative available for the systems being studied. Data sets were reviewed for completeness and material balances, and follow-up was conducted as needed to resolve any questions about the input and output flows, process technology, etc.

Reproducibility: To maximize transparency and reproducibility, the report identifies specific data sources, assumptions, and approaches used in the analysis to the extent possible; however, reproducibility of study results is limited to some extent by the need to protect proprietary primary data that were judged to be the most representative data sets for modeling purposes but could not be shown due to confidentiality.

Uncertainty: In LCA studies with thousands of numeric data points used in the calculations, the accuracy of the data and how it affects conclusions is truly a complex subject, and one that does not lend itself to standard error analysis techniques. Techniques such as Monte Carlo analysis can be used to assess study uncertainty, but the greatest challenge is the lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates. However, steps are taken to ensure the reliability of data and results, as previously described.

The accuracy of the environmental results depends on the accuracy of the numbers that are combined to arrive at that conclusion. For some processes, the data sets are based on actual plant data reported by plant personnel, while other data sets may be based on engineering estimates or secondary data sources. Primary data collected from actual facilities are considered the best available data for representing industry operations. In this study, primary data were used to model the reclaimer processes used to produce the recycled resins. All data received were carefully evaluated before compiling the production-weighted average data sets used to generate results. Supporting background data were drawn from credible, widely used databases including the US LCI database and ecoinvent.

1.3.5. Data Sources

Data sources used for modeling postconsumer resin collection, sorting, and recycling processes are listed in each section of Chapter 2. The recycled resin results are compared with corresponding virgin resin results modeled using data from the ACC resins report.[5]

1.3.6. Allocation Procedures

In some cases, a process may produce more than one useful output. The ISO 14044: 2006 standard on life cycle assessment requirements and guidelines lists the preferred hierarchy for handling allocation as (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. How product allocation is made will vary from one system to another, but the choice of parameter is not arbitrary. ISO 14044 section 4.3.4.2 states “the inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics.”

Some processes lend themselves to physical allocation because they have physical parameters that provide a good representation of the environmental burdens of each co-product. Examples of various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic allocation. In most cases, mass allocation has been used where allocation is necessary in this analysis. Allocation choices for specific processes are described in the rest of this section.

For material recovery facilities (MRFs), operating data were provided at a facility level, so it was not possible to allocate energy use to specific subprocesses or materials within the

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[5] Cradle-to-Gate Life Cycle Assessment of Nine Plastic Resins and Four Polyurethane Precursors. August 2011. Conducted by Franklin Associates, a Division of ERG for ACC Plastics Division. Available at https://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-Rpt-Only/

facility. Facility energy use and wastes were therefore allocated over the total mass of useful materials separated at the MRF.

Similarly, reclaimers provided operating data at a facility level. Reclaimers reported the amount of recycled resin produced, as well as the amounts of other useful material recovered from incoming material, including other resins, metals, etc. that are sold to other processors. The amount of material transported to the reclaimer also includes contaminants. The burdens associated with the contaminants in the incoming material (incoming transportation and contaminants removed as solid waste) were allocated over the total mass of useful material recovered from the incoming material. After sorting and separation, useful materials other than the intended resin type are sent to other locations for processing. Since the primary recycled resin is the only product that goes through the complete sequence of processing steps at the facility, all facility process requirements (energy, water and chemical use, emissions) were allocated to the primary resin output product.

In the sequence of processes used to produce virgin plastic resins from natural gas and petroleum feedstocks, some processes produce material or energy co-products. When the co-product is heat or steam or a co-product sold for use as a fuel, the energy content of the exported heat, steam, or fuel was treated as an energy credit for that process (i.e., allocation by energy content). When the co-product is a material, the process inputs and emissions were allocated to the primary product and co-product material(s) on a mass basis.

1.3.7. Recycling Methodology

When material is used in one system and subsequently recovered, reprocessed, and used in another application, there are different methods that can be used to allocate environmental burdens among different useful lives of the material.

This analysis presents results for two commonly used recycling allocation methodologies. Both of these methodological approaches are acceptable under the ISO standards; however, there are differences in the results obtained by using the two approaches.

In the method referred to here as the “cut-off” method, all virgin material production burdens are assigned to the first use of the material, and the burdens assigned to the recycled resin system begin with recovery of the postconsumer material. All of the burdens for material recovery, transport, separation and sorting, and reprocessing are assigned to the recycled material.

In the open-loop allocation method, the burdens for virgin material production, recovery and recycling, and ultimate disposal of recycled material are shared among all the sequential useful lives of the material. Therefore, the share of virgin material burdens allocated to any individual use of the resin depends upon assumptions about the total number of useful lives of the resin. This analysis does not define the application in which the recycled resin will be used, and no projections are made about future recovery and recycling of the material. For the purposes of presenting cradle-to-gate open-loop results for recycled resin, this analysis uses an assumption of **two** useful lives of the material (resin used in a virgin product, then in a recycled product, then disposed), so the burdens for virgin material production, postconsumer recovery, and reprocessing are divided between the virgin and recycled uses of the material.

Because this analysis is focused on production of resin used as an input to product manufacturing, no burdens are included here for manufacturing, use, or end-of-life management of a product made from the recycled resin. Those life cycle stages will depend on the specific product application in which the resin is being used.

1.3.8. Impact Assessment

The output of a life cycle inventory is a lengthy and diverse list of elementary and intermediate inputs and outputs, making it difficult to interpret the emissions inventory in a concise and meaningful manner. Life Cycle Impact Assessment (LCIA) helps with interpretation of the emissions inventory. LCIA is defined in ISO 14044 section 3.4 as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product." In the LCIA phase, the inventory of emissions is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

Characterization factors have been defined to estimate the amount of impact potential of LCI results. Impacts can be characterized as midpoint or endpoint indicators. The 'midpoint' approach links results to categories of commonly defined environmental concerns like eutrophication and climate change. The 'endpoint' approach further models the causality chain of environmental stressors to link LCI results to environmental damages (e.g., to human and ecosystem health). ISO standards allow the use of either method in the LCIA characterization step. Overall, indicators close to the inventory result (midpoint) have a higher level of scientific consensus, as less of the environmental mechanism is modeled. Conversely, endpoint and damage-oriented characterization models inevitably include much aggregation and some value-based weighting of parameters. To reduce uncertainty in communication of the results, this study focuses on indicators at the midpoint level.

1.3.8.1. Scope of Impact Assessment

This study evaluates a variety of environmental indicators for recycled resins. The indicators, along with brief descriptions, evaluation methodology, and reporting units, are shown in

Table 1-1.

Table 1-1. Environmental Indicators Evaluated

	Impact/Inventory Category	Description	Unit	LCIA/LCI Methodology
LCI Categories	**Total energy demand**	Total energy from point of extraction; results include both renewable and non-renewable energy sources	MJ	Cumulative energy inventory
	Expended energy	Energy irretrievably consumed; calculated as total energy minus the potentially recoverable energy embodied in the material.	MJ	Cumulative energy inventory minus energy embodied in material
	Water consumption	Freshwater withdrawals which are evaporated, incorporated into products and waste, transferred to different watersheds, or disposed into the sea after usage	liters H_2O	Cumulative water consumption inventory
	Solid waste by weight	Mass of waste materials sent to various waste management facilities (e.g., landfill, WTE) for final disposal	kg	Cumulative solid waste inventory
LCIA Categories	**Global warming potential (GWP)**	Represents the heat trapping capacity of greenhouse gases. Important emissions include fossil CO_2, CH_4, N_2O, fluorinated gases.	kg CO_2 equivalents (eq)	IPCC (2013) GWP 100a
	Acidification potential	Quantifies the acidifying effect of substances on their environment. Important emissions: SO_2, NO_x, NH_3, HCl, HF, H_2S	kg SO_2 eq	TRACI v2.1
	Eutrophication potential	Assesses impacts from excessive load of macro-nutrients to the environment. Important emissions: NH_3, NO_x, COD and BOD, N and P compounds	kg N eq	TRACI v2.1
	Smog formation potential	Determines the formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health and vegetation. Important emissions: NO_x, BTEX, NMVOC, CH_4, C_2H_6, C_4H_{10}, C_3H_8, C_6H_{14}, acetylene, Et-OH, formaldehyde	kg O_3 eq	TRACI v2.1

1.3.8.2. Energy Demand Accounting

ERG uses its own method to assess energy demand. The energy demand method is not an impact assessment, but rather is a cumulative inventory of energy extracted and utilized, including both renewable and non-renewable energy. Non-renewable fuels include fossil fuels (i.e., natural gas, petroleum, and coal) and nuclear energy, while fuels classified as renewable include hydroelectric energy, wind energy, hydropower, geothermal energy, and biomass energy.

Energy demand results include consumption of fuels for process and transportation energy, as well as the fuel-energy equivalent for materials that are derived from fossil fuels or biomass. The energy value of resources used as material feedstock is referred to as energy of material resource, or EMR. EMR is not expended energy (i.e., energy that is consumed through combustion) but the energy value of resources with fuel value (e.g., oil, natural gas) that are used to provide material content for virgin plastic resins. Some of this energy remains embodied in the material produced rather than being irretrievably expended through combustion, as is the case for process and transportation fuels. In this study, EMR applies to the crude oil and natural gas used to produce virgin plastic resins.

The energy values for fuels and electricity consumed in each industrial process are summed and categorized into an energy profile including the energy types (i.e., sources) listed below:

- Natural gas
- Petroleum
- Coal
- Nuclear
- Hydropower
- Biomass
- Other non-fossil
- Other fossil

The “other non-fossil” category includes sources such as solar, wind, and geothermal energy. The “other fossil” category refers to other fuels derived from fossil fuel sources such as combustion of fossil-derived plastics and rubbers in municipal solid waste. All conversions for fuel inputs reflect the fuels’ higher heating values (HHV).

CHAPTER 2. RECOVERY AND RECYCLING PROCESSES

2.1. INTRODUCTION

In this analysis, the steps for production of postconsumer recycled resin are divided into three main stages:

(1) Recovery: Collection of postconsumer plastic,
(2) Sorting and Separation: Sorting of plastics from other co-collected recovered materials (such as paper, steel, and aluminum), and separating mixed plastics into individual resins,
(3) Reclaimer Operations: Additional separation and processing of postconsumer resin by a reclaimer to convert the received material into clean resin ready for use in manufacturing.

This chapter describes the methodology and data sources used to quantify each stage.

2.2. RECOVERY

Postconsumer PET, HDPE and PP products that are recovered for recycling are primarily packaging products, including soft drink and milk bottles, other bottles and containers, and other PET and HDPE packaging, such as PET thermoforms. Collection of these materials occurs through residential curbside collection, drop-off programs, deposit redemption systems, and commercial collection programs. The percentage of containers recovered through the California deposit system is shown as “CRV” (California refund value) in Table 2-1.

The percent of PET, HDPE and PP recovery through the various collection programs was determined from an analysis of the following data sources:

National PET, HDPE and PP Recovery for 2015:

- U.S. EPA. Advancing Sustainable Materials Management: Facts and Figures 2015. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management

Curbside/Drop-off/Deposit Mix:

- Governmental Advisory Associates, Inc. 2016-2017 Materials Recycling and Processing in the United States Database. 2016.
- California Department of Resources Recycling and Recovery. November 7, 2016. Biannual Report of Beverage Container Sales, Returns, Redemption, and Recycling Rates. Accessed 16 February 2017. http://www.calrecycle.ca.gov
- California Department of Conservation Division of Recycling. June 2009. Market Analysis for Recycled Beverage Container Materials: 2009 Update. Accessed 16 February 2017 http://www.calrecycle.ca.gov/Publications/Documents/BevContainer/2011024.pdf

Commercial Recovery:

- PET and HDPE containers calculated as total recovery minus residential recovery and deposit recovery
- PP commercial recovery assumed to be negligible.

The results of this analysis are shown below.

Table 2-1. Collection Systems for Recovery of Postconsumer PET, HDPE, and PP Containers and Other Packaging

	Curbside (1)	Drop-off	Deposit (2)	CRV (3)	Commercial	
					Through MRF	Other
PET	54%	5%	17%	16%	2%	6%
HDPE (4)	62%	5%	5%	4%	23%	2%
PP	95%	5%		<0.1%		

(1) Includes deposit and non-deposit containers collected through curbside.
(2) Includes deposit and non-deposit containers collected through deposit centers.
(3) California refund value
(4) Excludes HDPE film packaging.

The following sections describe how fuel use for each type of collection was estimated for this analysis. Some of the estimates utilize default data from the U.S. EPA Municipal Solid Waste (MSW) Decision Support Tool (DST):

> U.S. EPA. Office of Research and Development, APPCD. *Default Data and Data Input Requirement for the Municipal Solid Waste Management Decision Support Tool Final*. December 2000. https://webdstmsw.rti.org/docs/Inputs_Document_OCR.pdf

2.2.1. Fuel Use for Residential Curbside Collection

Residential curbside collection accounts for the majority of postconsumer plastic recovery (over 50 percent of PET, over 60 percent of HDPE, and 95 percent of the PP). To develop fuel requirements for curbside collection of PET, HDPE, and PP, data were gathered from various sources to determine the percentage of material collected curbside for three levels of separation: single stream, dual stream, and curbside sort. Single stream and dual stream were further divided into manual and automated collection. Curbside sort is manual.

Curbside collection modeling was developed from the following data sources:

Collection System – Percentages of Single Stream, Dual Stream, Curbside Sort; **Percentages of Automated/Manual Collection**

- Governmental Advisory Associates, Inc. 2016-2017 Materials Recycling and Processing in the United States Database. 2016.

Collection System – Fuel Profile:

- Environmental Research & Education Foundation (EREF) and University of Central Florida. Ergonomic & Environmental Study of Solid Waste Collection Final Report. November 8, 2012.
- Texas Gas Service. Refuse Companies Waste No Time Switching to CNG. (undated).
- Clean Energy Compression. What Refuse Truck Fleets are doing to Make Our Air Cleaner. July 30, 2015.

The total quantity of recyclables per truckload was based on the number of households served per collection vehicle route, the average pounds of recyclables set out per household per week, and the composition of the recyclables generated. The truck fuel requirements were then allocated to the materials collected. The following data sources were used:

Composition by Weight of Materials Collected per Vehicle Load:

- U.S. EPA. Advancing Sustainable Materials Management: Facts and Figures 2015. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management
- California Department of Conservation Division of Recycling. June 2009. Market Analysis for Recycled Beverage Container Materials: 2009 Update. Accessed 16 February 2017. http://www.calrecycle.ca.gov/Publications/Documents/BevContainer/2011024.pdf

The results of this analysis are shown in Table 2-2.

Collection route planning is typically based on the number of household stops that can be made by the vehicle, taking into account the level of automation of the vehicle (affecting time spent per stop) and the volume of material that will be collected from the households on the route. Consumer compaction of recyclables prior to set-out can vary widely depending on household practices. Additional compaction of the material is done by the compaction mechanism on the collection vehicle. The fuel profile of collection vehicles was modeled as 96 percent trucks using diesel fuel at 2.80 mpg and 4 percent vehicles using compressed natural gas (CNG) at 2.47 mpg. This include fuel use while idling at stops, as well as fuel used while the vehicle is traveling.

Table 2-2. Curbside Collection Profile by Weight

	Single stream collection		Dual stream collection		Curbside sort collection
Percent of Material Collected	91.8%		6.9%		1.3%
	27.7%	64.1%	5.2%	1.7%	1.3%
Truck type	Manual	Fully/semi-Automated	Manual	Fully/semi-automated	Manual
Route distance round trip	50	50	50	50	50
Households per route	710	1,200	800	1,000	560
Set-out rate	57%	57%	57%	57%	57%
Average set-outs per route	405	684	456	570	319
Pounds material per set-out	12.5	12.5	9.5	9.5	7.3
Pounds material per load	5,044	8,526	4,325	5,407	2,331
Truck Load Composition (by weight)*					
PET	**2.8%**	**2.8%**	**2.8%**	**2.8%**	**3.6%**
HDPE	**1.5%**	**1.5%**	**1.5%**	**1.5%**	**2.0%**
PP	**0.3%**	**0.3%**	**0.3%**	**0.3%**	**0.4%**
Other plastic	0.9%	0.9%	0.9%	0.9%	
ONP (old newspaper)	28.3%	28.3%	28.3%	28.3%	36.8%
Corrugated containers	4.8%	4.8%	4.8%	4.8%	6.2%
Other paper	28.7%	28.7%	29.7%	28.7%	37.2
Aluminum	1.3%	1.3%	1.3%	1.3%	1.7%
Steel	5.8%	5.8%	5.8%	5.8%	7.5%
Glass	3.5%	3.5%	3.5%	3.5%	4.5%
Other packaging	11.4%	11.4%	11.4%	11.4%	
Nonrecyclables	10.7%	10.7%	10.7%	10.7%	
Total	100%	100%	100%	100%	100%
*Curbside sort individual percentages are higher due to fewer materials in the curbside sort mix compared to single and dual stream.					

2.2.2. Fuel Use for Consumer Drop-off at a Recycling Center

As shown in Table 2-1, drop-off recycling centers account for approximately 5 percent of postconsumer plastic recovery. Fuel use by consumers delivering household recyclables to a drop-off center was estimated based on following assumptions:

- 12.5 pounds of household recyclables generated per week (EPA MSW report and weekly set-out rate shown in Table 2-2)
- Recyclables dropped off every other week (ERG assumption)
- Distance driven: 10 miles (EPA MSW Decision Support Tool default value)

- Fuel economy of personal vehicle used for trip: 22 mpg (EPA Greenhouse Gases Equivalencies Calculator - Calculations and References[6])
- Percent of trips that are dedicated trips for the purpose of dropping off recyclables: 50% (MSW DST default)
- Remainder of trips are assumed to have a different primary purpose so that drop-off of recyclables requires incremental additional travel, estimated as 5 miles, to make an extra stop at a drop-off center (ERG assumption).

2.2.3. Deposit and CRV Drop-off

It is assumed that a consumer would not make a trip for the sole purpose of returning deposit containers. Consumers would drop off bottles as an incidental stop on a trip with some other primary purpose (e.g., deposit bottles purchased at a grocery store would be returned on the next trip to the store to buy groceries), so fuel use for returning deposit containers is treated as incidental, with no consumer transport burdens assigned to returning deposit containers. Accumulated quantities of deposit containers are modeled as being transported from the collection point to an intermediate processing center (IPC). Based on information provided by a confidential source, transport of deposit containers to the IPC is modeled as a volume-limited load of loose bottles transported 20 miles by a single-unit truck. At the IPC, the containers are baled for shipment to the next processing location.

2.2.4. Commercial Collection

No consumer transport burdens are assigned to postconsumer plastic recovered from commercial sources. For this scenario, it is assumed that the accumulated quantities transported per load are larger and a tractor-trailer truck is used. Based on information provided by a confidential source, the distance hauled is longer and is estimated as 150 miles. At the MRF some additional sorting may be done before the postconsumer material is baled for shipment to the next processing location.

2.3. SORTING AND SEPARATION

Once the postconsumer PET, HDPE, and PP have been collected, they must be separated from other co-collected materials and plastics. Although some recovered plastic is separated by curbside sorting and the use of separate bins at drop-off recycling centers, sorting and separation of plastics most commonly takes place at material recovery facilities (MRFs). Sorting operations at MRFs range from manual sorting of items on a conveyor to highly automated systems using magnets, air classifiers, optical sorters, and other technologies to sort and separate mixed incoming materials. Postconsumer plastics may be separated and baled as mixed plastics, or the facility may have the capability to further sort down to individual resin bales.

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[6] Accessed at https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references. “In 2015, the weighted average fuel economy of cars and light trucks combined was 22.0 miles per gallon (FHWA 2017).”

For the original (2011) recycled resin analysis, data were collected from MRFs and a PRF using data collection forms developed specifically for the project by ERG. Four completed MRF surveys and one completed PRF survey were received. For the MRFs, one data set was for a large facility that processed both single-stream and dual-stream collected material, two were for medium dual-stream facilities, and one was for a small dual-stream facility. The data provided on the forms included information on the sources of material received at the MRF, the transportation mode and distance for incoming material from each source, the types and quantities of useful materials recovered from the incoming material, the types of equipment used at the facility, energy and water use at the facility, and the solid wastes, atmospheric and waterborne emissions from the facility. For each facility, the operating data were allocated over the total weight of recovered materials.

Individual MRF facility data cannot be shown because of data confidentiality; however, a weighted average data set was developed based on the amount of collected plastic material processed at each type of facility, using the single- and dual-stream collection data from section 2.1. The weighted average data set is shown in Table 2-3. To protect confidential data, the PRF data set cannot be shown.

Table 2-3. Sorting at MRF

	Per 1000 lb	Per 1 kg
Incoming Material		
Collected postconsumer resin (1)	1,100 lb	1.10 kg
Energy		
Electricity	6.56 kWh	0.014 kWh
Natural gas	0.052 cu ft	3.3E-06 cu m
Diesel	0.24 gal	0.0020 liter
LPG	0.40 gal	0.0033 liter
Solid Waste		
Incoming wastes removed at MRF	100 lb	0.1 kg

---

(1) Includes the weight of incoming contaminants removed at the MRF.

For sorting at MRFs, total solid wastes were allocated over the total pounds of useful output, so that the pounds of MRF sorting waste is the same for 1,000 pounds of output, whether it is PET, HDPE, PP. The same approach was used to calculate the sorting waste per 1,000 pounds of output material for the PRF.

2.4. RECLAIMER OPERATIONS

Data collection forms for PET, HDPE, and PP reclaimers were developed for this project by ERG. Completed forms were received from seven PET reclaimer facilities, six facilities processing HDPE, and three PP reclaimers. The data sets were used to compile a weighted average for each resin based on each facility's recycled resin output as a percentage of the total output of that recycled resin for all reporting facilities. As with the MRF data sets, only the weighted average data sets can be shown in order to protect the confidentiality of individual facility data sets.

While the majority of reclaimers participating in this analysis were located in the US, some data were provided by reclaimers in Canada and Mexico. The weighted average electricity shown in the reclaimer tables does not separate out the weighted average amounts of electricity use by country, to prevent any possibility of backing out individual reclaimer electricity use based on their share of recycled resin production. The results in Chapter 3 reflect the weighted average mix of electricity for resin produced in each country.

2.4.1. PET Reclamation Processes

The reclaimers that provided data for this study produced over 416 million pounds of clean PET flake and converted 337 million pounds of flake to solid stated food grade pellet. The average incoming transport distance to reclaimers was 366 miles by truck. Overall, the participating reclaimers reported receiving about 90% of incoming shipments from MRFs, 8.7% from deposit centers, and less than 1% from PRFs. Impacts for collection of material prior to shipment to the reclaimer were based on the industry average profile described in section 2.2. Reclaimers reported that the majority of the incoming material was bottles (95%), with the remainder thermoforms.

Most of the reporting facilities receive postconsumer PET as individual resin bales. Bales are broken down and the material sorted to remove foreign material. Some reclaimers pre-wash sorted material before it is flaked, and some reclaimers receive some resin at already in flake form. Incoming flake may be clean or dirty, but all reclaimed flake is washed to market specifications as part of reclaimer processing operations. This is most often achieved with a caustic wash, but different reclaimers reported using a variety of washing chemicals including surfactants, defoamers, and wetting agents.

Even though the incoming material has undergone some presorting before it is received, other materials are mixed in with the incoming PET. Some of the non-PET material is saleable, such as polyolefin cap material (HDPE, PP) and aluminum, while other materials are unusable contaminants. Non-PET saleable materials comprised, on average, about 14% of the weight of incoming material received, while unusable contaminants accounted for an average of 15% of the weight of incoming material.

Clean postconsumer PET can be sold in flake form, or it can be pelletized, with or without solid stating. Depending on the level of processing, the postconsumer PET resin may be used for food-grade or non-food applications. All reclaimers who reported processing clean flake to pellet produced food-grade LNO pellet. Most reclaimers reported solid stating the material in flake form, then converting to pellet, but some reported solid stating in pellet form.

Material and energy requirements per 1,000 pounds of postconsumer PET flake output are listed in the top of Table 2-4, and process data for converting flake to food-grade pellet are reported in the bottom of the table. Data are presented in both US and metric units.

2.4.2. HDPE Reclamation Processes

HDPE reclaimers providing data for this analysis produced 448 million pounds of clean flake and converted 427 million pounds of flake to pellet. The weighted average incoming transport profile of postconsumer material was 350 miles by truck and 134 miles by rail. A small amount of ocean transport was also reported. Approximately 92% of incoming material was shipped to participating reclaimers from MRFs, 6% from deposit centers, and less than 1% each from PRFs and other sources. The majority of the incoming material was reported as bottles (82%), with the remainder rigids.

As with PET, incoming bales are broken down and the material sorted to remove foreign material. Processing steps include debaling, grinding, washing, drying, extruding and pelletizing. A small amount of reclaimed resin was reported as received already in flake form (weighted average less than 3%). Material may be washed before grinding, after grinding, or both. Most reclaimers reported using a variety of chemicals in the washing process, although types and quantities varied by reclaimer.

Incoming HDPE material contains small amounts of non-HDPE saleable material as well as unusable contaminants. The weighted average percentage of non-HDPE saleable material recovered from incoming bales was less than 1%, while 17% of the incoming material was unusable contaminants.

The weighted average material and energy requirements for producing 1,000 pounds of postconsumer recycled HDPE flake are listed in the top section of Table 2-5, and energy use for pelletizing is reported in the bottom section of the table.

Table 2-4. PET Reclaimer Operations

	Per 1000 lb	Per 1 kg
Bale to Flake		
Incoming Material		
Collected and sorted postconsumer resin (1)	1,178 lb	1.18 kg
Chemical Inputs		
Sodium hydroxide, 50%	9.50 lb	0.0095 kg
Washing agents (2)	2.67 lb	0.0027 kg
Defoamants	3.08 lb	0.0031 kg
Chemicals with aluminum compounds	0.68 lb	6.8E-04 kg
Ferric chloride	0.068 lb	6.8E-05 kg
Hydrogen peroxide, 35%	0.0054 lb	5.4E-06 kg
Acid	0.99 lb	0.0010 kg
Salt	0.48 lb	4.8E-04 kg
Wastewater treatment polymer	0.10 lb	9.9E-05 kg
Other confidential chemicals	0.018 lb	1.8E-05 kg
Water consumption	105 gal	0.88 liters
Energy		
Electricity (3)	155 kWh	0.34 kWh
Natural gas	1,070 cu ft	0.067 cu m
Diesel	0.079 gal	6.6E-04 liter
LPG	0.13 gal	0.0011 liter
Propane	0.37 gal	0.0031 liter
Incoming Transportation		
Combination truck transport, diesel (resin)	216 ton miles	0.70 tonne-km
Combination truck transport, diesel (chemicals)	1.01 ton miles	0.0033 tonne-km
Solid Waste		
Incoming contaminants removed by reclaimer (4)	178 lb	0.18 kg
Wastes generated by reclamation processes	11.5 lb	0.011 kg
Emissions to air		
Particulates, unspecified	0.0074 lb	7.4E-06 kg
Emissions to water		
BOD (Biological Oxygen Demand)	1.83 lb	0.0018 kg
COD (Chemical Oxygen Demand)	1.57 lb	0.0016 kg
Suspended solids, unspecified	0.78 lb	7.8E-04 kg
Dissolved solids, unspecified	0.036 lb	3.6E-05 kg
Flake to Pellet		
Process Inputs		
Nitrogen	50.3 cu ft	0.0031 cu m
Energy		
Electricity (3)	218 kWh	0.48 kWh
Natural gas	549 cu ft	0.034 cu m
LPG	0.010 gal	8.3E-05 liter
Propane	0.035 gal	2.9E-04 liter

---

(1) Incoming transport of resin includes the weight of incoming contaminants allocated to the resin based on its share of total weight of saleable outputs (resin and other recovered materials).

(2) Washing agents include a variety of detergents and surfactants; not listed individually due to confidentiality.

(3) Includes electricity reported by participating reclaimers in US, Canada, and Mexico; kWh by country not listed individually to protect confidentiality.

(4) Weight of contaminants in incoming material allocated to the resin based on its share of total weight of saleable outputs (resin and other recovered materials).

Table 2-5. HDPE Reclaimer Operations

	Per 1000 lb	Per 1 kg
Bale to Flake		
Incoming Material		
Collected and sorted postconsumer resin (1)	1,192 lb	1.19 kg
Chemical Inputs		
Sodium hydroxide, 50%	2.35 lb	0.0023 kg
Washing agents (2)	1.99 lb	0.0020 kg
Defoamants	1.49 lb	0.0015 kg
Chemicals with aluminum compounds	0.27 lb	2.7E-04 kg
Ferric chloride	0.0043 lb	4.3E-06 kg
Hydrogen peroxide, 35%	2.9E-05 lb	2.9E-08 kg
Sodium hypochlorite, 12.5%	0.14 lb	1.4E-04 kg
Acid	0.047 lb	4.7E-05 kg
Wastewater treatment polymer	0.0089 lb	8.9E-06 kg
Water consumption	104 gal	0.87 liters
Energy		
Electricity (3)	87.8 kWh	0.19 kWh
Natural gas	168 cu ft	0.010 cu m
Diesel	0.043 gal	3.6E-04 liter
LPG	0.015 gal	1.3E-04 liter
Propane	0.14 gal	0.0011 liter
Incoming Transportation		
Combination truck transport, diesel (resin)	209 ton miles	0.67 tonne-km
Rail transport (resin)	79.9 ton miles	0.26 tonne-km
Average ocean freighter transport (resin)	11.2 ton miles	0.036 tonne-km
Combination truck transport, diesel (chemicals)	0.35 ton miles	0.0011 tonne-km
Solid Waste		
Incoming contaminants removed by reclaimer (4)	192 lb	0.19 kg
Wastes generated by reclamation processes	26.2 lb	0.026 kg
Emissions to air		
None reported		
Emissions to water		
BOD (Biological Oxygen Demand)	0.31 lb	3.1E-04 kg
COD (Chemical Oxygen Demand)	0.54 lb	5.4E-04 kg
Suspended solids, unspecified	0.42 lb	4.2E-04 kg
Dissolved solids, unspecified	0.10 lb	1.0E-04 kg
Flake to Pellet		
Energy		
Electricity (3)	151 kWh	0.33 kWh

---

(1) Incoming transport of resin includes the weight of incoming contaminants allocated to the resin based on its share of total weight of saleable outputs (resin and other recovered materials).

(2) Washing agents include a variety of detergents and surfactants; not listed individually due to confidentiality.

(3) All participating reclaimers were located in the US.

(4) Weight of contaminants in incoming material allocated to the resin based on its share of total weight of saleable outputs (resin and other recovered materials).

2.4.3. PP Reclamation Processes

Because only three facilities provided data on PP recycling, and not all the facilities converted clean flake to pellet, limited details can be provided about PP reclaimer operations in order to protect confidentiality of individual reclaimer data. A minimum of three data sets are required to compile a weighted average that can be shown separately while protecting individual data providers' confidential information.

PP reclaimers providing data for this analysis produced 142 million pounds of clean flake. To protect confidential information, the amount of pellet cannot be shown because less than three participating reclaimers reported converting flake to pellet. The weighted average incoming transport profile of postconsumer material was 408 miles by truck and 154 miles by rail. About 90% of incoming material was shipped to participating reclaimers from MRFs, less than 3% from PRFs, and 6% from other sources. The incoming material was divided fairly evenly between bottles and rigids. On average, less than 1% of the incoming material was non-PP saleable material and almost 15% was contaminants. Reclaimers reported little use of chemicals.

The combined weighted average material and energy requirements for producing 1,000 pounds of postconsumer recycled PP pellet are listed in Table 2-6. Because less than three reclaimers reported converting flake to pellet, it is not possible to show separate weighted averages for clean flake processing and pelletizing of clean flake.

Table 2-6. PP Reclaimer Operations

Bale to Pellet	**Per 1000 lb**		**Per 1 kg**	
Incoming Material				
Collected and sorted postconsumer resin (1)	1,172	lb	1.17	kg
Chemical Inputs				
Sodium hydroxide, 50%	0.69	lb	6.9E-04	kg
Washing agents (2)	1.68	lb	0.0017	kg
Defoamants	1.48	lb	0.0015	kg
Water consumption	124	gal	1.03	liters
Energy				
Electricity (3)	240	kWh	0.53	kWh
Natural gas	395	cu ft	0.025	cu m
Diesel	0.097	gal	8.1E-04	liter
LPG	0.074	gal	6.2E-04	liter
Incoming Transportation				
Combination truck transport, diesel (resin)	239	ton miles	0.77	tonne-km
Rail transport (resin)	90.2	ton miles	0.29	tonne-km
Solid Waste				
Incoming contaminants removed by reclaimer (4)	172	lb	0.17	kg
Wastes generated by reclamation processes	25.1	lb	0.025	kg
Emissions to air				
None reported				
Emissions to water				
BOD (Biological Oxygen Demand)	0.0055	lb	5.5E-06	kg
COD (Chemical Oxygen Demand)	0.25	lb	2.5E-04	kg
Suspended solids, unspecified	0.20	lb	2.0E-04	kg

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(1) Incoming transport of resin includes the weight of incoming contaminants allocated to the resin based on its share of total weight of saleable outputs (resin and other recovered materials).

(2) Washing agents include a variety of detergents and surfactants; not listed individually due to confidentiality.

(3) Includes electricity reported by participating reclaimers in the US and Canada; kWh by country not listed individually to protect confidentiality.

(4) Weight of contaminants in incoming material allocated to the resin based on its share of total weight of saleable outputs (resin and other recovered materials).

CHAPTER 3. RESULTS

3.1. INTRODUCTION

This chapter presents the energy requirements, water consumption, solid wastes, and other emission-related environmental impacts for the sequence of processes used to collect, transport, separate, and process postconsumer PET, HDPE, and PP into clean recycled resin ready for use to manufacture a plastic product. The process data sets for each step were presented in Chapter 2. The production and combustion of fuels used for process and transportation energy and generation of U.S. grid electricity were modeled using data sets developed by ERG for the US LCI Database. The recycled resin production data are compared to virgin PET, HDPE, and PP results modeled using data from the ACC 2011 resins database.

As noted in Chapter 2 section 2.4, the majority of reclaimers participating in this analysis were located in the US; however, some data were provided by reclaimers in Canada and Mexico. The results in this chapter reflect the weighted average mix of electricity for the share of recycled resin production by participating reclaimers in each country.

3.2. RECYCLING METHODOLOGIES

As described in the **Postconsumer Recycling** section of Chapter 1, results are presented for two commonly used recycling allocation methodologies, cut-off and open-loop. While both methodological approaches are acceptable under ISO LCA standards, there are differences in the results obtained by using the two approaches.

In the cut-off method, all virgin material production burdens are assigned to the first use of the material, and all burdens for material recovery, transport, separation and sorting, and reprocessing are assigned to the recycled material.

In the open-loop allocation method, the burdens for virgin material production, recovery and recycling, and ultimate disposal of recycled material are shared among all the sequential useful lives of the material. For the purposes of presenting cradle-to-gate open-loop results for recycled resin, this analysis uses an assumption of two useful lives of the material (resin used in a virgin product, then in a recycled product, with no projections about any further recycling after the second use). For two useful lives of the resin, half of the burdens for virgin material production, postconsumer recovery, and reprocessing are assignedto the first use of the resin and half is assigned to its recycled use. When recycled resin data are used for open-loop modeling of product systems, the number of useful lives of the material should be adjusted as appropriate if there is recycling of the secondary product at the end of its useful life.

To summarize, the recycled resin results presented in this chapter represent the following:

- Cut-off method: Full burdens for collection, sorting, and reclaimer operations; no virgin resin burdens
- Open-loop method: Half burdens for virgin resin production, collection, sorting, and reclaimer operations

Because this analysis is focused on production of resin used as an input to product manufacturing, no burdens are included here for manufacturing, use, or end-of-life management of a product made from the recycled resin. Those life cycle stages will depend on the specific product application in which the resin is being used.

3.3. LIFE CYCLE INVENTORY RESULTS

For each recycled resin, the results tables and figures break out results by several life cycle stages:

- Collection and sorting of postconsumer plastic,
- Transport to reclaimer,
- Impacts for process water and chemicals used at reclaimer,
- Process energy to convert incoming material to clean flake,
- Process energy to convert clean flake to pellet,
- Process emissions and wastes from reclaimer operations.

Each set of tables and figures shows results for both recycling allocation methods described above (cut-off and open-loop). The top section of each table shows results for the cut-off method, and the bottom section shows results for the open-loop method. Each section shows results for 1 kg resin and for 1,000 lb resin. In each table, the virgin resin data results were modeled using virgin resin data sets from the ACC resin report from 2011, with electricity grid modeling updated to represent 2014 generation. Because virgin resin impacts are generally greater than impacts for collection and recycling processes, results for the open-loop method with an allocated share of virgin resin production burdens are generally higher than results for the cut-off method. Exceptions are seen in a few cases.

3.3.1. Energy Results

Cumulative energy demand results include all renewable and non-renewable energy sources used for process and transportation energy, as well as material feedstock energy. Process energy includes direct use of fuels as well as use of fossil fuels, hydropower, nuclear, wind, solar, and other energy sources to generate electricity used by processes. The feedstock energy is the energy content of the resources removed from nature and used as material feedstocks (e.g., the energy content of oil and gas resources used as material feedstocks to produce virgin resins).

Total energy results for recycled and virgin resins are shown in Table 3-1 and Figure 3-1. The total energy results shown in Figure 3-1 for virgin resin include the feedstock energy embodied in the resin, and feedstock energy is also included in the allocated virgin resin burdens in the open-loop recycled resin results. Total energy requirements for food-grade rPET pellet are 21 percent of virgin PET resin burdens when the cut-off recycling method is used, and 61 percent of virgin resin energy using the open-loop recycling allocation method. For HDPE and PP, recycled HDPE and PP pellets require 12 percent as much energy as virgin resin using the cut-off recycling method, and 56 percent as much energy as virgin for the open-loop recycling method.

Table 3-1. Total Energy Results for Recycled Resin Compared to Virgin, With and Without Feedstock Energy

	PC Resin Collection & Sorting	PC Resin Transport to Reclaimer	Process Water & Chemicals	Process Energy, Bale to Flake	Process Energy, Flake to Pellet*	Process Emissions & Wastes	Recycled Resin Pellet Total**	Virgin Pellet (including Feedstock Energy)	Recycled % of Virgin	Recycled Resin % Reduction from Virgin	Virgin Pellet (excluding Feedstock Energy)	Recycled % of Virgin	Recycled Resin % Reduction from Virgin
CUT-OFF													
MJ per kg of resin													
Recycled PET	1.19	0.87	0.21	6.44	6.14	0	**14.8**	**69.8**	21%	79%	**33.3**	45%	55%
Recycled HDPE	1.52	0.92	0.13	2.55	3.57	0	**8.69**	**75.3**	12%	88%	**25.0**	35%	65%
Recycled PP	1.64	1.04	0.11	6.09		0	**8.89**	**74.4**	12%	88%	**25.1**	35%	65%
Million Btu per 1000 lb of resin													
Recycled PET	0.51	0.37	0.089	2.77	2.64	0	**6.38**	**30.0**	21%	79%	**14.3**	45%	55%
Recycled HDPE	0.65	0.40	0.058	1.10	1.53	0	**3.74**	**32.4**	12%	88%	**10.8**	35%	65%
Recycled PP	0.71	0.45	0.049	2.62		0	**3.82**	**32.0**	12%	88%	**10.8**	35%	65%
OPEN LOOP													
MJ per kg of resin													
Recycled PET	0.60	0.43	0.10	3.22	3.07	0	**42.3**	**69.8**	61%	39%	**33.3**	72%	28%
Recycled HDPE	0.76	0.46	0.067	1.27	1.78	0	**42.0**	**75.3**	56%	44%	**25.0**	67%	33%
Recycled PP	0.82	0.52	0.057	3.04		0	**41.6**	**74.4**	56%	44%	**25.1**	68%	32%
Million Btu per 1000 lb of resin													
Recycled PET	0.26	0.19	0.044	1.38	1.32	0	**18.2**	**30.0**	61%	39%	**14.3**	72%	28%
Recycled HDPE	0.33	0.20	0.029	0.55	0.77	0	**18.0**	**32.4**	56%	44%	**10.8**	67%	33%
Recycled PP	0.35	0.22	0.024	1.31		0	**17.9**	**32.0**	56%	44%	**10.8**	68%	32%

*For PP, only combined results for bale to pellet are shown in order to protect confidential data from participating reclaimers.

**In Open-loop results, recycled resin total includes allocated share of virgin resin impacts.

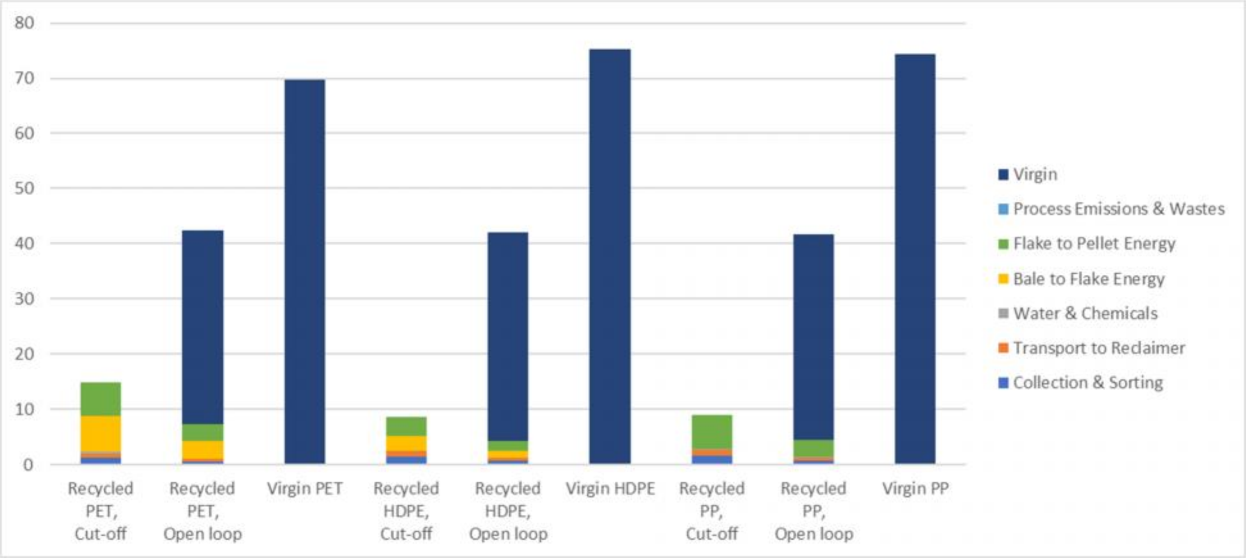

Figure 3-1. Total Energy Results for Recycled and Virgin Resins (MJ/kg)

Figure 3-2 shows comparative results for recycled and virgin burdens with feedstock energy embodied in the resin excluded, so that the results represent the expended process and transportation energy that is consumed in producing virgin and recycled resins. The results in Figure 3-2 are shown on the same scale as the results in Figure 3-1. Because feedstock energy accounts for a significant share of the total energy requirements for virgin resin, excluding feedstock energy in the virgin resin significantly reduces the overall results for virgin resin as well as open-loop results for recycled resin that include an allocated share of virgin impacts. When virgin and recycled resins are compared on the basis of process and transportation energy consumed, cut-off results for recycled PET are 45 percent of virgin PET energy, and cut-off results for recycled HDPE and PP are 35 percent of virgin energy. Open-loop results for recycled resins as a percentage of corresponding virgin resin results are 72 percent for PET, 67 percent for HDPE, and 68 percent for PP.

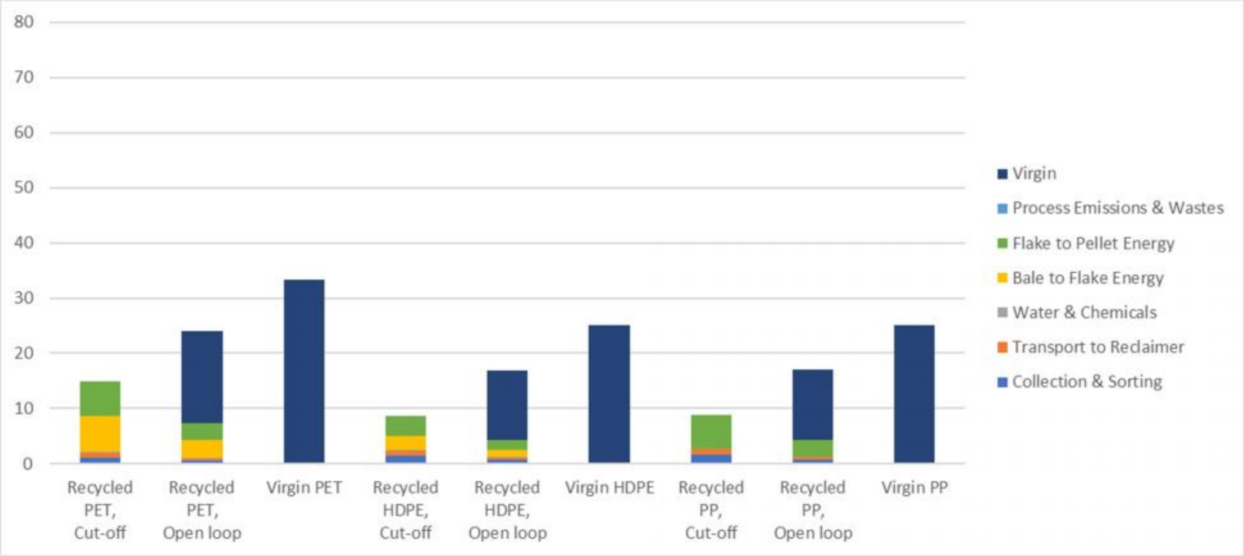

Figure 3-2. Process and Transportation Energy for Recycled and Virgin Resins Excluding Feedstock Energy (MJ/kg)

3.3.2. Water Consumption Results

Consumptive use of water in this study includes freshwater that is withdrawn from a water source or watershed and not returned to that source. Consumptive water use includes water consumed in chemical reactions, water that is incorporated into a product or waste stream, water that becomes evaporative loss, and water that is discharged to a different watershed or water body than the one from which it was withdrawn. Water consumption results shown for each life cycle stage include process water consumption as well as water consumption associated with production of the electricity and fuels used in that stage. Electricity-related water consumption includes evaporative losses associated with thermal generation of electricity from fossil and nuclear fuels, as well as evaporative losses due to establishment of dams for hydropower.

Water consumption results for recycled and virgin resins are shown in Table 3-2 and Figure 3-3. The figure shows that water consumption associated with energy use for flake and pellet processing steps is greater than direct water consumption for washing and flotation separation operations at reclaimer facilities. Water consumption results for flake and pellet processing include evaporative losses of cooling water associated with electricity generation via fossil fuel combustion, as well as evaporative losses from reservoirs used for hydropower generation. Hydropower accounts for a significant share of the electricity used by reclaimers in Canada.

Water consumption results for food-grade rPET pellet are 104 percent of virgin PET resin burdens when the cut-off recycling method is used, and 102 percent of virgin resin energy using the open-loop recycling allocation method. For HDPE, recycled resin pellets consume 41 percent as much water as virgin resin using the cut-off recycling method, and 71 percent as much water as virgin for the open-loop recycling method. For PP, recycled resin pellets consume 54 percent as much water as virgin resin using the cut-off recycling method, and 77 percent as much water as virgin for the open-loop recycling method.

Table 3-2. Water Consumption Results for Recycled Resin Compared to Virgin

	PC Resin Collection & Sorting	PC Resin Transport to Reclaimer	Process Water & Chemicals	Process Energy, Bale to Flake	Process Energy, Flake to Pellet*	Process Emissions & Wastes	Recycled Resin Pellet Total**	Virgin Pellet	Recycled % of Virgin	Recycled Resin % Reduction from Virgin
CUT-OFF										
Liters of water per kg of resin										
Recycled PET	0.19	0.11	1.37	2.92	5.73	0	**10.3**	**9.89**	104%	-4%
Recycled HDPE	0.23	0.11	0.90	0.82	1.37	0	**3.43**	**8.33**	41%	59%
Recycled PP	0.25	0.13	1.05	3.22		0	**4.65**	**8.58**	54%	46%
Gallons of water per 1000 lb of resin										
Recycled PET	22.8	12.6	164	350	687	0	**1,236**	**1,186**	104%	-4%
Recycled HDPE	27.8	13.4	108	98.1	164	0	**411**	**998**	41%	59%
Recycled PP	29.7	15.2	126	386		0	**557**	**1,028**	54%	46%
OPEN LOOP										
Liters of water per kg of resin										
Recycled PET	0.095	0.053	0.68	1.46	2.87	0	**10.1**	**9.89**	102%	-2%
Recycled HDPE	0.12	0.056	0.45	0.41	0.68	0	**5.88**	**8.33**	71%	29%
Recycled PP	0.12	0.063	0.53	1.61		0	**6.62**	**8.58**	77%	23%
Gallons of water per 1000 lb of resin										
Recycled PET	11.4	6.30	81.9	175	344	0	**1,211**	**1,186**	102%	-2%
Recycled HDPE	13.9	6.71	53.9	49.1	81.9	0	**704**	**998**	71%	29%
Recycled PP	14.8	7.61	63.1	193		0	**793**	**1,028**	77%	23%

*For PP, only combined results for bale to pellet are shown in order to protect confidential data from participating reclaimers.

**In Open-loop results, recycled resin total includes allocated share of virgin resin impacts.

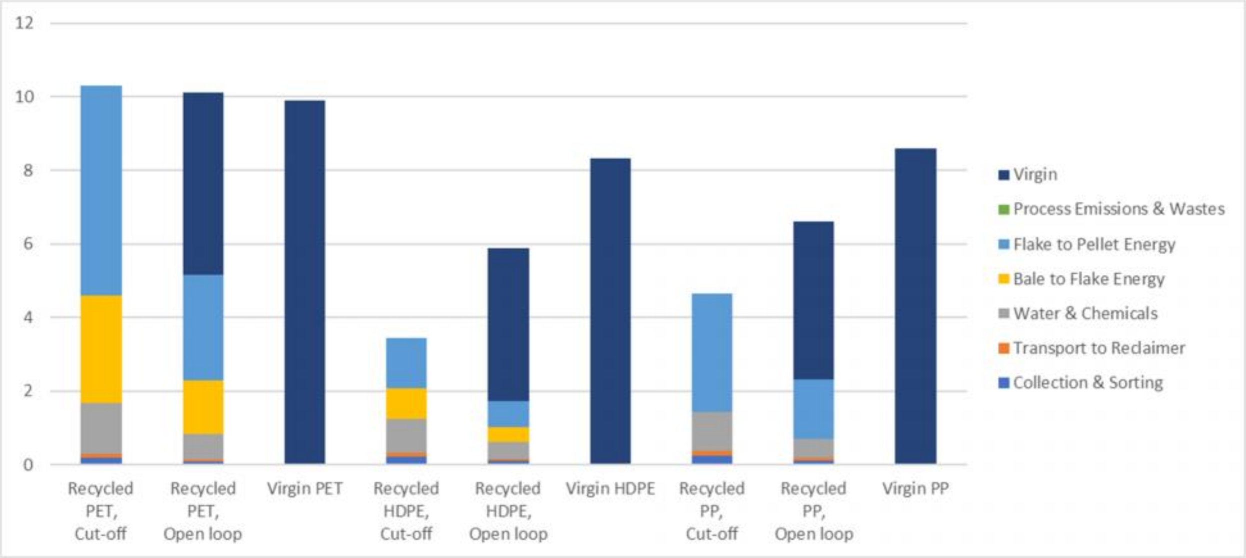

Figure 3-3. Water Consumption Results for Recycled and Virgin Resins (liters water/kg resin)

3.3.3. Solid Waste Results

Solid waste includes sludges and residues from chemical reactions and material processing steps, wastes associated with production and combustion of fuels (e.g., refinery wastes, coal combustion ash from power generation), and waste materials removed from collected postconsumer material.

Total solid waste results for recycled and virgin resins are shown in Table 3-3 and Figure 3-4. The results include the weight of contaminants in the material received by MRFs and reclaimers. The contaminants are separated from the received material during sorting and separation processes. The contaminant wastes make large contributions to the total solid wastes for recycled resins, as shown in Figure 3-4.

Although the contaminant wastes are removed and disposed at reclaimer facilities, these wastes are not *caused* by reclaimer operations. Reclaimers recover all saleable materials from the incoming material, including materials other than the desired resin. Therefore, the majority of the solid waste disposed from the sorting and processing operations is material that would have been disposed as waste regardless of whether postconsumer plastic recycling takes place. If incoming contaminant wastes are excluded, the process solid wastes for recycled resins drop dramatically, as can be seen by comparing Figure 3-5 with Figure 3-4.

With incoming contaminant wastes excluded, total solid waste results for food-grade rPET pellet are 42 percent of virgin PET resin burdens when the cut-off recycling method is used, and 71 percent of virgin resin solid waste using the open-loop recycling allocation method. Recycled HDPE solid wastes are essentially the same as virgin HDPE solid wastes for both recycling methodologies. Recycled PP pellets result in 77 percent as much solid waste as virgin resin using the cut-off recycling method, and 88 percent as much waste as virgin for the open-loop recycling method.

Table 3-3. Solid Waste Results for Recycled Resin Compared to Virgin, With and Without Incoming Contaminants

	PC Resin Collection & Sorting	PC Resin Transport to Reclaimer	Process Water & Chemicals	Process Energy, Bale to Flake	Process Energy, Flake to Pellet*	Process Emissions & Wastes	Recycled Resin Pellet Total w/ Incoming Contam**	Virgin Pellet	Recycled Total Compared to Virgin	Recycled Total w/o Incoming Contam	Recycled % of Virgin
CUT-OFF											
Kg solid waste per kg of resin											
Recycled PET	0.15	8.3E-04	4.4E-04	0.020	0.022	0.19	**0.39**	**0.14**	2.8	**0.058**	42%
Recycled HDPE	0.24	8.9E-04	2.3E-04	0.015	0.025	0.22	**0.50**	**0.070**	7.1	**0.071**	101%
Recycled PP	0.27	0.0010	1.9E-04	0.030		0.20	**0.50**	**0.078**	6.4	**0.060**	77%
Pounds of solid waste per 1000 lb of resin											
Recycled PET	155	0.83	0.44	20.1	22.5	190	**388**	**136**	2.8	**57.7**	42%
Recycled HDPE	236	0.89	0.23	15.0	25.3	219	**496**	**70.2**	7.1	**70.6**	101%
Recycled PP	269	1.01	0.19	30.2		197	**498**	**77.9**	6.4	**59.6**	77%
OPEN LOOP											
Kg solid waste per kg of resin											
Recycled PET	0.077	4.2E-04	2.2E-04	0.010	0.011	0.095	**0.26**	**0.14**	1.9	**0.097**	71%
Recycled HDPE	0.12	4.4E-04	1.2E-04	0.0075	0.013	0.11	**0.28**	**0.070**	4.0	**0.070**	100%
Recycled PP	0.13	5.0E-04	9.3E-05	0.015		0.099	**0.29**	**0.078**	3.7	**0.069**	88%
Pounds of solid waste per 1000 lb of resin											
Recycled PET	77	0.42	0.22	10.0	11.2	94.8	**262**	**136**	1.9	**97.0**	71%
Recycled HDPE	118	0.44	0.12	7.49	12.6	109	**283**	**70.2**	4.0	**70.4**	100%
Recycled PP	134	0.50	0.093	15.1		98.7	**288**	**77.9**	3.7	**68.8**	88%

*For PP, only combined results for bale to pellet are shown in order to protect confidential data from participating reclaimers.

**In Open-loop results, recycled resin total includes allocated share of virgin resin impacts.

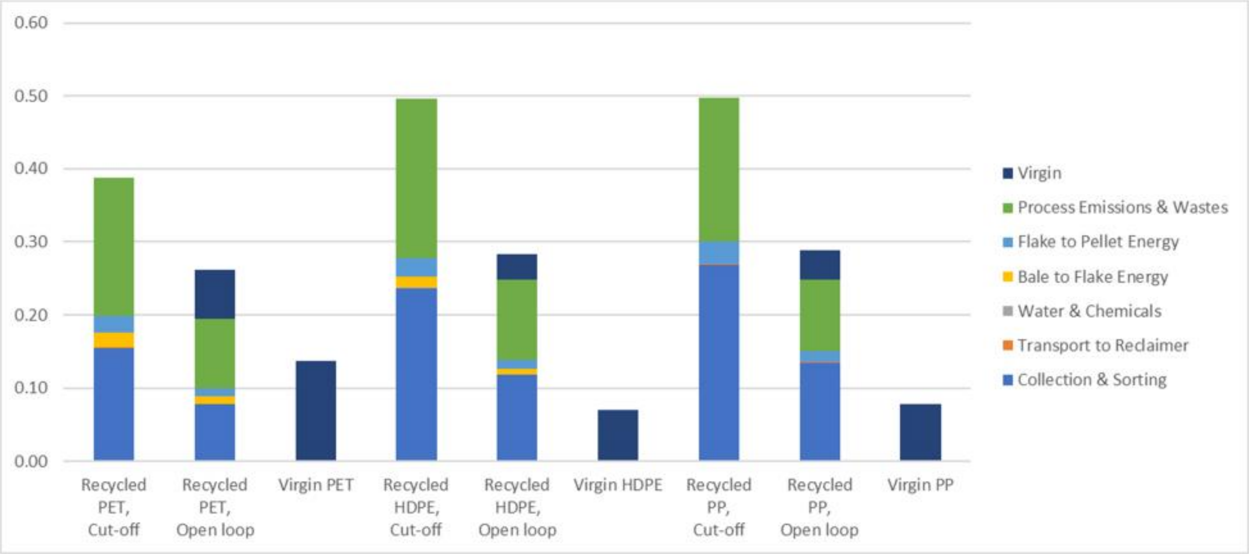

Figure 3-4. Solid Waste Results for Recycled and Virgin Resins, Including Contaminants in Incoming Material (kg waste/kg resin)

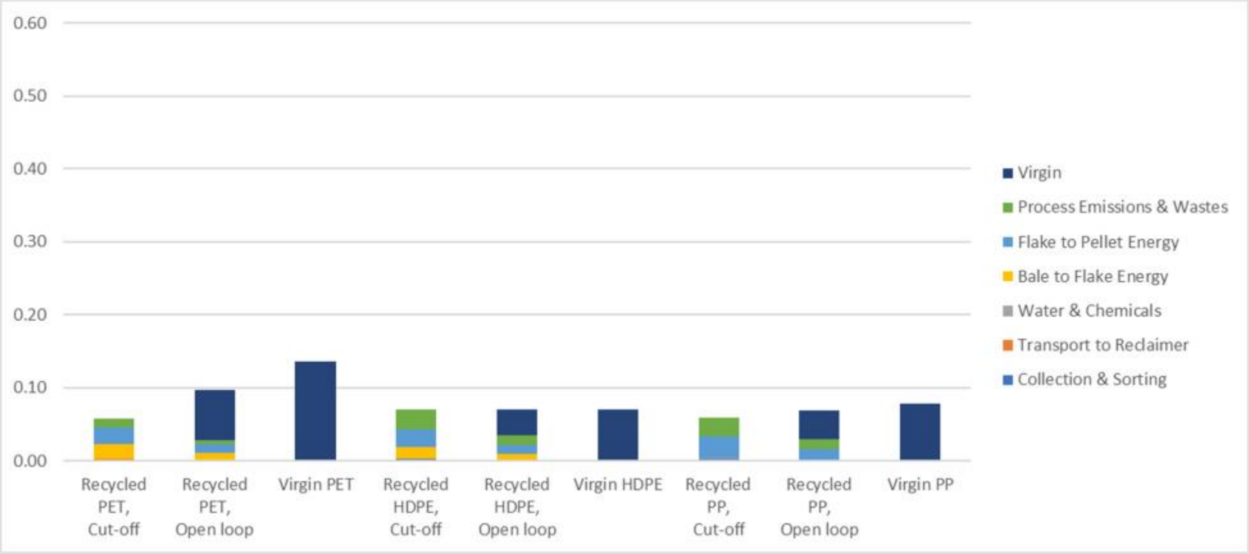

Figure 3-5. Solid Waste Results for Recycled and Virgin Resins, Excluding Contaminants in Incoming Material (kg waste/kg resin)

3.4. LIFE CYCLE IMPACT ASSESSMENT RESULTS

Atmospheric and waterborne emissions for each system include emissions from processes as well as emissions associated with the combustion of fuels. **Process emissions** refers to emissions released directly from the processes that are used to extract, transform, convert, or otherwise effect changes on a material during its life cycle, while **fuel-related emissions** are those associated with the combustion of fuels used for process energy and transportation energy.

In the LCIA phase, the inventory of process and fuel-related emissions is classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance. The following sections present results for the LCIA results categories analyzed.

3.4.1. Global Warming Potential (GWP) Results

Life cycle global warming potential results include the impacts of process emissions (e.g., fugitive or direct emissions from chemical reactions or converting operations), emissions from the extraction, processing, and combustion of fuels used for process and transportation energy, and emissions from extraction and processing of fossil fuels used as material feedstocks.

Global warming potential results for recycled and virgin resins are shown in Table 3-4 and Figure 3-6. For the cut-off recycling methodology, results for recycled PET are 33 percent of virgin PET GWP, and recycled HDPE and PP results are 29 percent of virgin. Open-loop results for all three recycled resins are 64-66 percent of the corresponding virgin resins. Reclaimer energy use (for converting incoming material to clean flake and converting flake to pellet) account for the majority of GWP impacts for recycled resin production steps.

Table 3-4. Global Warming Potential Results for Recycled Resin Compared to Virgin

	PC Resin Collection & Sorting	PC Resin Transport to Reclaimer	Process Water & Chemicals	Process Energy, Bale to Flake	Process Energy, Flake to Pellet*	Process Emissions & Wastes	Recycled Resin Pellet Total**	Virgin Pellet	Recycled % of Virgin	Recycled Resin % Reduction from Virgin
CUT-OFF										
kg CO2 eq per kg of resin										
Recycled PET	0.082	0.060	0.0088	0.40	0.36	0	**0.91**	**2.78**	33%	67%
Recycled HDPE	0.10	0.064	0.0064	0.16	0.22	0	**0.56**	**1.89**	29%	71%
Recycled PP	0.11	0.073	0.0054	0.33		0	**0.53**	**1.84**	29%	71%
kg CO2 eq per 1000 lb of resin										
Recycled PET	37.0	27.4	4.00	181	165	0	**415**	**1,262**	33%	67%
Recycled HDPE	47.4	29.2	2.91	72.1	100	0	**252**	**857**	29%	71%
Recycled PP	51.3	33.1	2.45	152		0	**239**	**835**	29%	71%
OPEN LOOP										
kg CO2 eq per kg of resin										
Recycled PET	0.041	0.030	0.0044	0.20	0.18	0	**1.85**	**2.78**	66%	34%
Recycled HDPE	0.052	0.032	0.0032	0.079	0.11	0	**1.22**	**1.89**	65%	35%
Recycled PP	0.057	0.036	0.0027	0.17		0	**1.18**	**1.84**	64%	36%
kg CO2 eq per 1000 lb of resin										
Recycled PET	18.5	13.7	2.00	90.5	82.7	0	**838**	**1,262**	66%	34%
Recycled HDPE	23.7	14.6	1.46	36.0	50.2	0	**554**	**857**	65%	35%
Recycled PP	25.6	16.5	1.22	75.9		0	**537**	**835**	64%	36%

*For PP, only combined results for bale to pellet are shown in order to protect confidential data from participating reclaimers.

**In Open-loop results, recycled resin total includes allocated share of virgin resin impacts.

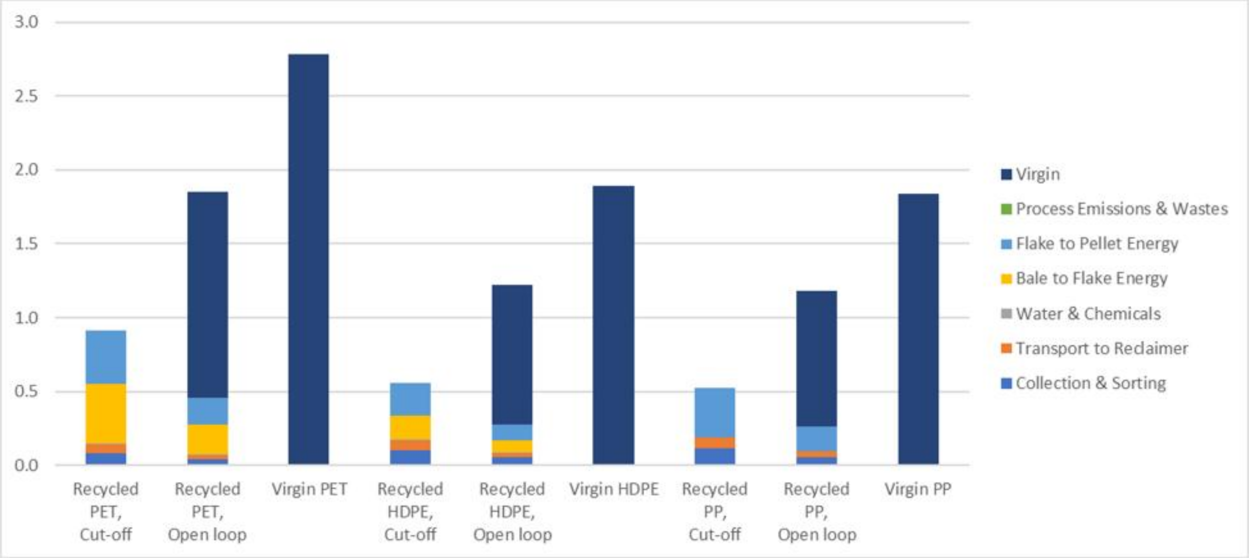

Figure 3-6. Global Warming Potential Results for Recycled and Virgin Resins (kg CO_2 eq/kg resin)

3.4.2. Acidification Potential Results

Acidification assesses the potential of emissions to contribute to the formation and deposit of acid rain on soil and water, which can cause serious harm to plant and animal life as well as damage to infrastructure. Acidification potential modeling in TRACI incorporates the results of an atmospheric chemistry and transport model, developed by the U.S. National Acid Precipitation Assessment Program (NAPAP), to estimate total North American terrestrial deposition due to atmospheric emissions of NO_x and SO_2, as a function of the emissions location.[7,8]

Acidification impacts are typically dominated by fossil fuel combustion emissions, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Emissions from combustion of fossil fuels, especially coal, to generate grid electricity are a significant contributor to acidification impacts.

Acidification potential results for recycled and virgin resins are shown in Table 3-4 and Figure 3-7. Results for food-grade rPET pellet are 30 percent of virgin PET resin burdens when the cut-off recycling method is used and 65 percent of virgin resin acidification using the open-loop recycling allocation method. For recycled HDPE, cut-off results are 53 percent of virgin results and 77 percent of virgin for open-loop. Recycled PP results are 42 percent of virgin using the cut-off recycling method and 71 percent of virgin for the open-loop recycling method.

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[7] Bare J.C., Norris G.A., Pennington D.W., McKone T. (2003). TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology*, **6**(3–4): 49–78. Available at URL: http://mitpress.mit.edu/journals/pdf/jiec_6_3_49_0.pdf.

[8] Bare J.C. (2002). Developing a consistent decision-making framework by using the US EPA's TRACI, AICHE. Available at URL: http://www.epa.gov/nrmrl/std/sab/traci/aiche2002paper.pdf.

Table 3-5. Acidification Potential Results for Recycled Resin Compared to Virgin

	PC Resin Collection & Sorting	PC Resin Transport to Reclaimer	Process Water & Chemicals	Process Energy, Bale to Flake	Process Energy, Flake to Pellet*	Process Emissions & Wastes	Recycled Resin Pellet Total**	Virgin Pellet	Recycled % of Virgin	Recycled Resin % Reduction from Virgin
CUT-OFF										
kg SO2 eq per kg of resin										
Recycled PET	2.7E-04	2.5E-04	5.0E-05	0.0013	0.0014	0	**0.0032**	**0.011**	30%	70%
Recycled HDPE	3.5E-04	3.4E-04	2.0E-05	8.3E-04	0.0014	0	**0.0029**	**0.0055**	53%	47%
Recycled PP	3.8E-04	3.7E-04	1.5E-05	0.0017		0	**0.0025**	**0.0059**	42%	58%
kg SO2 eq per 1000 lb of resin										
Recycled PET	0.12	0.11	0.023	0.58	0.62	0	**1.46**	**4.80**	30%	70%
Recycled HDPE	0.16	0.16	0.0092	0.38	0.62	0	**1.32**	**2.48**	53%	47%
Recycled PP	0.17	0.17	0.0066	0.78		0	**1.12**	**2.67**	42%	58%
OPEN LOOP										
kg SO2 eq per kg of resin										
Recycled PET	1.4E-04	1.2E-04	2.5E-05	6.4E-04	6.8E-04	0	**0.0069**	**0.011**	65%	35%
Recycled HDPE	1.7E-04	1.7E-04	1.0E-05	4.2E-04	6.8E-04	0	**0.0042**	**0.0055**	77%	23%
Recycled PP	1.9E-04	1.8E-04	7.3E-06	8.6E-04		0	**0.0042**	**0.0059**	71%	29%
kg SO2 eq per 1000 lb of resin										
Recycled PET	0.062	0.056	0.011	0.29	0.31	0	**3.13**	**4.80**	65%	35%
Recycled HDPE	0.079	0.078	0.0046	0.19	0.31	0	**1.90**	**2.48**	77%	23%
Recycled PP	0.086	0.083	0.0033	0.39		0	**1.89**	**2.67**	71%	29%

*For PP, only combined results for bale to pellet are shown in order to protect confidential data from participating reclaimers.

**In Open-loop results, recycled resin total includes allocated share of virgin resin impacts.

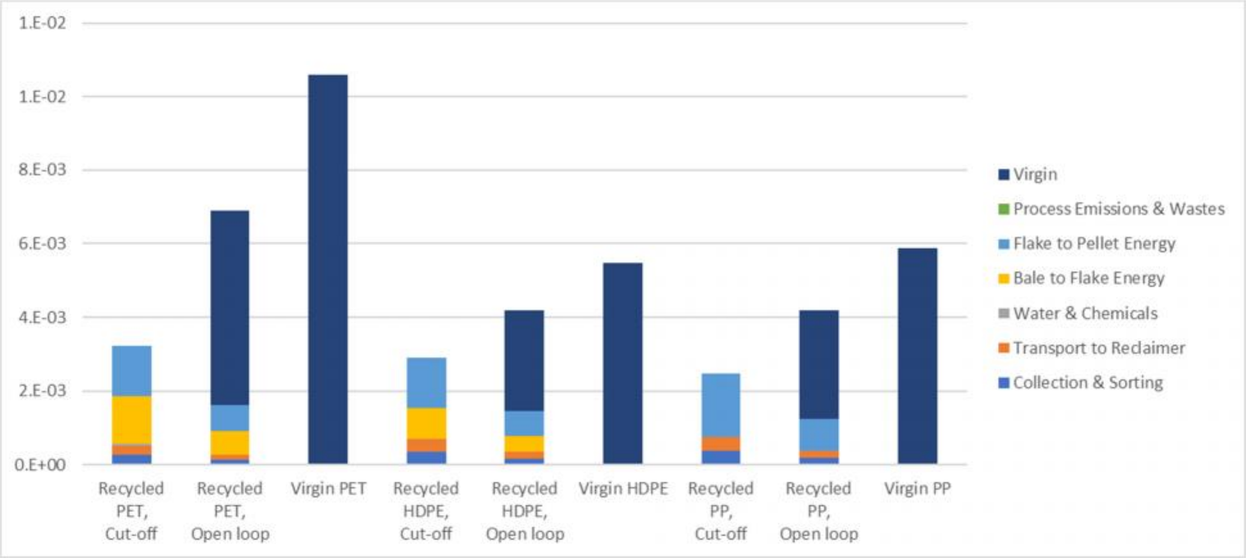

Figure 3-7. Acidification Potential Results for Recycled and Virgin Resins (kg SO_2 eq/kg resin)

3.4.3. Eutrophication Potential Results

Eutrophication occurs when excess nutrients are introduced to surface water causing the rapid growth of aquatic plants. This growth (generally referred to as an “algal bloom”) reduces the amount of dissolved oxygen in the water, thus decreasing oxygen available for other aquatic species. The TRACI characterization factors for eutrophication are the product of a nutrient factor and a transport factor.[9] The nutrient factor is based on the amount of plant growth caused by each pollutant, while the transport factor accounts for the probability that the pollutant will reach a body of water. Atmospheric emissions of nitrogen oxides (NO_x) as well as waterborne emissions of nitrogen, phosphorus, ammonia, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are typically the main contributors to eutrophication impacts.

Eutrophication potential results for recycled and virgin resins are shown in Table 3-6 and Figure 3-8. Process emissions in wastewater are the largest contribution to eutrophication results for recycled PET and HDPE, while PP reclaimers reported low wastewater emissions.

Eutrophication results for recycled PET and PP pellet are 54-57 percent of corresponding virgin resin burdens when the cut-off recycling methodology is used, and 77-79 percent of virgin resin eutrophication using the open-loop recycling allocation methodology. Eutrophication results for recycled HDPE for both recycling methodologies are essentially the same as virgin HDPE.

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[9] Bare J.C., Norris G.A., Pennington D.W., McKone T. (2003). TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology*, **6**(3–4): 49–78. Available at URL: http://mitpress.mit.edu/journals/pdf/jiec_6_3_49_0.pdf.

Table 3-6. Eutrophication Potential Results for Recycled Resin Compared to Virgin

	PC Resin Collection & Sorting	PC Resin Transport to Reclaimer	Process Water & Chemicals	Process Energy, Bale to Flake	Process Energy, Flake to Pellet*	Process Emissions & Wastes	Recycled Resin Pellet Total**	Virgin Pellet	Recycled % of Virgin	Recycled Resin % Reduction from Virgin
CUT-OFF										
kg N eq per kg of resin										
Recycled PET	1.2E-05	1.4E-05	1.5E-05	2.5E-05	2.6E-05	1.7E-04	**2.6E-04**	**4.8E-04**	54%	46%
Recycled HDPE	1.5E-05	1.8E-05	1.8E-06	1.4E-05	2.2E-05	4.2E-05	**1.1E-04**	**1.1E-04**	102%	-2%
Recycled PP	1.7E-05	2.0E-05	7.8E-07	2.9E-05		1.3E-05	**8.0E-05**	**1.4E-04**	57%	43%
kg N eq per 1000 lb of resin										
Recycled PET	0.0053	0.0062	0.0068	0.011	0.012	0.077	**0.12**	**0.22**	54%	46%
Recycled HDPE	0.0070	0.0084	8.2E-04	0.0064	0.010	0.019	**0.052**	**0.051**	102%	-2%
Recycled PP	0.0077	0.0092	3.6E-04	0.013		0.0059	**0.036**	**0.064**	57%	43%
OPEN LOOP										
kg N eq per kg of resin										
Recycled PET	5.8E-06	6.8E-06	7.5E-06	1.3E-05	1.3E-05	8.5E-05	**3.7E-04**	**4.8E-04**	77%	23%
Recycled HDPE	7.7E-06	9.2E-06	9.0E-07	7.1E-06	1.1E-05	2.1E-05	**1.1E-04**	**1.1E-04**	101%	-1%
Recycled PP	8.5E-06	1.0E-05	3.9E-07	1.5E-05		6.5E-06	**1.1E-04**	**1.4E-04**	79%	21%
kg N eq per 1000 lb of resin										
Recycled PET	0.0026	0.0031	0.0034	0.0057	0.0058	0.039	**0.17**	**0.22**	77%	23%
Recycled HDPE	0.0035	0.0042	4.1E-04	0.0032	0.0050	0.0096	**0.051**	**0.051**	101%	-1%
Recycled PP	0.0039	0.0046	1.8E-04	0.0066		0.0029	**0.050**	**0.064**	79%	21%

*For PP, only combined results for bale to pellet are shown in order to protect confidential data from participating reclaimers.

**In Open-loop results, recycled resin total includes allocated share of virgin resin impacts.

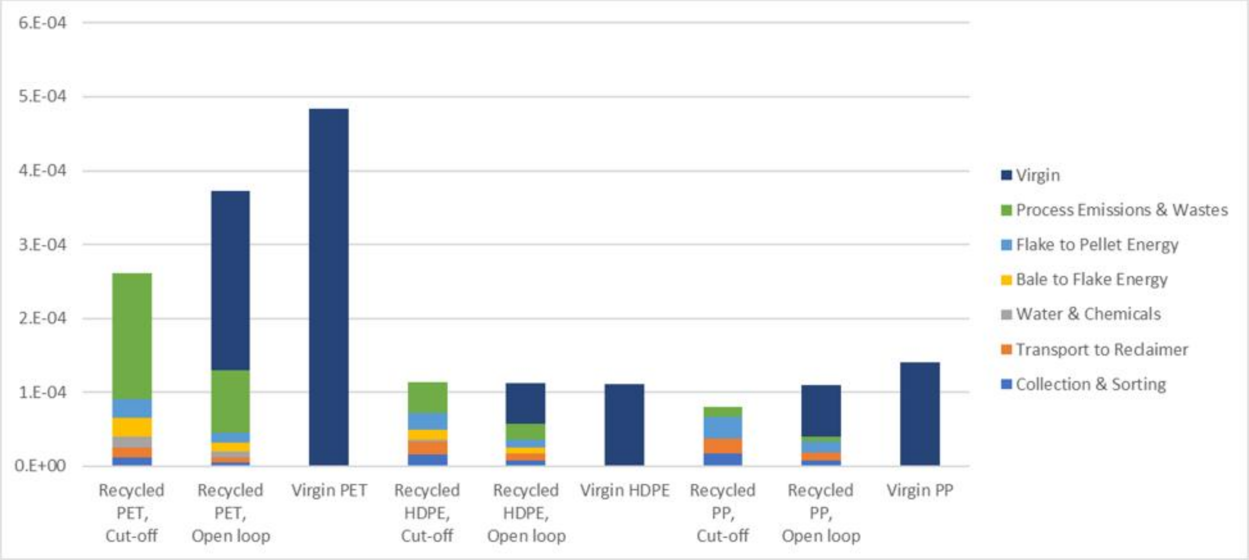

Figure 3-8. Eutrophication Potential Results for Recycled and Virgin Resins (kg N eq/kg resin)

3.4.4. Smog Formation Potential Results

The smog formation impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth. Smog formation impacts, like the other atmospheric impact indicators included in this study, are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements.

Smog potential results for recycled and virgin resins are shown in Table 3-7 and Figure 3-9. Results for food-grade rPET pellet are 25 percent of virgin PET resin burdens when the cut-off recycling method is used, and 63 percent of virgin resin smog potential using the open-loop recycling allocation method. Recycled HDPE results in 63 percent as much smog formation potential as virgin resin using the cut-off recycling method, and 82 percent as much smog potential as virgin for the open-loop recycling method. Recycled PP results using the cut-off recycling method are 50 percent of virgin smog formation results, and open-loop results are 75 percent of virgin results.

Table 3-7. Smog Potential Results for Recycled Resin Compared to Virgin

	PC Resin Collection & Sorting	PC Resin Transport to Reclaimer	Process Water & Chemicals	Process Energy, Bale to Flake	Process Energy, Flake to Pellet*	Process Emissions & Wastes	Recycled Resin Pellet Total**	Virgin Pellet	Recycled % of Virgin	Recycled Resin % Reduction from Virgin
CUT-OFF										
kg O3 eq per kg of resin										
Recycled PET	0.0063	0.0074	4.8E-04	0.014	0.014	0	**0.043**	**0.17**	25%	75%
Recycled HDPE	0.0083	0.010	3.1E-04	0.0079	0.012	0	**0.039**	**0.062**	63%	37%
Recycled PP	0.0092	0.011	2.5E-04	0.016		0	**0.037**	**0.073**	50%	50%
kg O3 eq per 1000 lb of resin										
Recycled PET	2.86	3.37	0.22	6.37	6.50	0	**19.3**	**76.6**	25%	75%
Recycled HDPE	3.78	4.61	0.14	3.60	5.56	0	**17.7**	**28.0**	63%	37%
Recycled PP	4.19	5.03	0.11	7.42		0	**16.8**	**33.3**	50%	50%
OPEN LOOP										
kg O3 eq per kg of resin										
Recycled PET	0.0031	0.0037	2.4E-04	0.0070	0.0072	0	**0.11**	**0.17**	63%	37%
Recycled HDPE	0.0042	0.0051	1.5E-04	0.0040	0.0061	0	**0.050**	**0.062**	82%	18%
Recycled PP	0.0046	0.0055	1.3E-04	0.0082		0	**0.055**	**0.073**	75%	25%
kg O3 eq per 1000 lb of resin										
Recycled PET	1.43	1.68	0.11	3.19	3.25	0	**47.9**	**76.6**	63%	37%
Recycled HDPE	1.89	2.30	0.070	1.80	2.78	0	**22.8**	**28.0**	82%	18%
Recycled PP	2.09	2.52	0.057	3.71		0	**25.0**	**33.3**	75%	25%

*For PP, only combined results for bale to pellet are shown in order to protect confidential data from participating reclaimers.

**In Open-loop results, recycled resin total includes allocated share of virgin resin impacts.

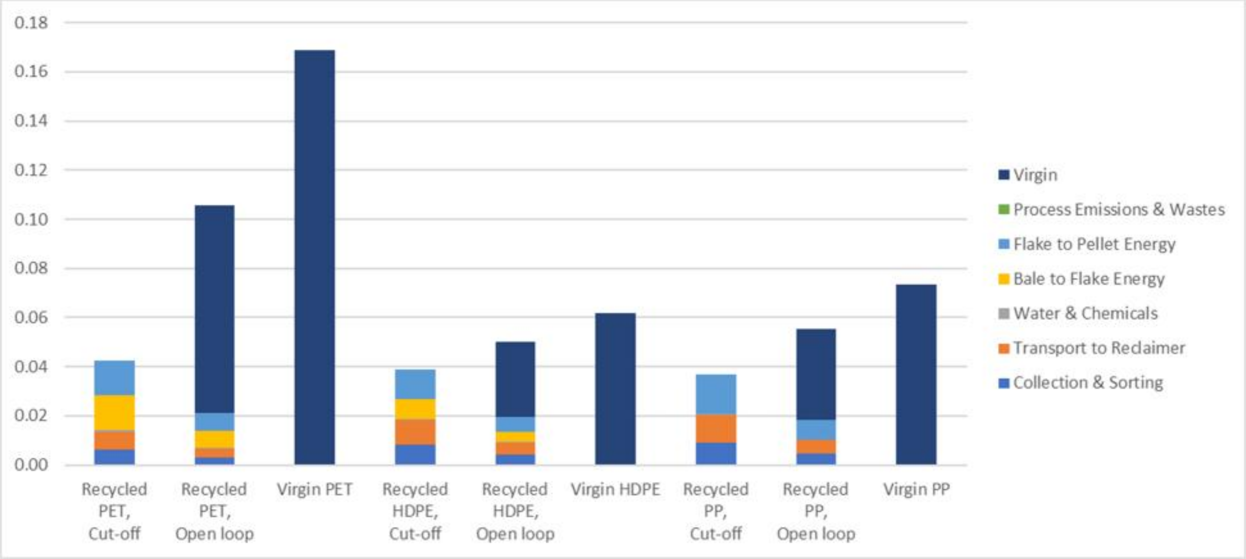

Figure 3-9. Smog Potential Results for Recycled and Virgin Resins ($kg\ O_3\ eq/kg\ resin$)

3.5. EQUIVALENCIES

In the preceding sections, the results for recycled resin compared to virgin resin are expressed on the basis of 1 kg and 1,000 pounds. To provide a better sense of the magnitude of savings achieved by recycling plastics on a national level, the 1,000 pound savings for each resin were scaled up to the amount of PET, HDPE, and PP packaging recovered from the US municipal solid waste supply in 2015.[10] The total amounts of recovered plastic packaging (excluding film) were 940,000 short tons of PET packaging, 580,000 short tons of HDPE packaging, and 70,000 short tons of PP packaging.

The savings for US packaging recycling can be visualized using equivalency factors. The equivalency factors used are listed below. Table 3-8 shows the recycled resin savings for 2015 US recovered plastic packaging expressed as equivalencies.

- The total energy savings for recycled resins compared to virgin is expressed as equivalent number of US households' annual electricity use, using information from the US EPA Greenhouse Gas Equivalencies Calculator.[11] Average electricity use per household is reported as 12,148 kWh year. Multiplied by 3,412 Btu/kWh, the average electricity use per household is equivalent to 41.45 million Btu. For the total amount of US PET, HDPE, and PP packaging recovered in 2015, Table 3-8 shows that total energy savings using cut-off recycling methodology are 81.5

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[10] Advancing Sustainable Materials Management: 2015 Tables and Figures. Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States. July 2018. Recovery of PET, HDPE, and PP packaging shown in Table 8. Accessed at https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf

[11] Home Electricity Use section of https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

trillion Btu, equivalent to almost 2 million households' annual electricity use, and the savings using open-loop recycling methodology total 40.8 trillion Btu, equivalent to 983 million households' electricity use.

- Savings in water consumption for recycled resins compared to virgin can be visualized as the equivalent number of Olympic swimming pools holding 2,500,000 liters of water.[12] For the total amount of PET, HDPE, and PP packaging recovered in the US in 2015, water consumption savings using cut-off recycling methodology are 652 million liters, equivalent to 261 Olympic pools, and the savings using open-loop recycling methodology are 326 million liters, equivalent to 130 pools.
- Solid waste savings are expressed as the equivalent number of 747 airplanes with an empty weight of 402,300 pounds.[13] For the total 2015 recovery of US PET, HDPE, and PP packaging, solid waste savings (excluding incoming contaminant wastes) using cut-off recycling methodology are almost 150 million pounds, equivalent to 372 747 airplanes, and the savings using open-loop recycling methodology are 74.9 million pounds, equivalent to the weight of 186 747s.
- The GWP savings can be visualized as the emissions from the equivalent number of personal vehicles driven per year, using factors from the US EPA Greenhouse Gas Equivalencies Calculator.[14] For the total amount of US packaging recovered in 2015, recycled resin GHG savings using the cut-off method are 2.4 million metric tons CO_2 eq, which is equivalent to the GHG emissions saved by taking over 500,000 passenger vehicles off the road for a year. For open-loop recycled resin results compared to virgin, the total GHG savings are 1.2 million metric tons CO_2 eq, equivalent to the GHG emissions saved by taking 254,000 passenger vehicles off the road for a year.

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[12] Olympic pool dimensions 50 meters long x 25 meters wide x 2 meters deep. http://www.dimensionsinfo.com/olympic-pool-size-dimensions/

[13] Empty weight of 747-400 is 402,300 pounds per http://www.boeing.com/resources/boeingdotcom/company/about_bca/startup/pdf/historical/747-400-passenger.pdf

[14] Emissions calculated as 4.67 tons CO2 eq/vehicle/year in Passenger Vehicles per Year section of https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Table 3-8. Recycled Resin Savings for 2015 US Recovered Packaging Volume

	Total Energy	Water Consumption	Solid Waste (excluding contaminants)	Global Warming Potential	EPA 2015 Plastic Packaging Recovery*
	million Btu	liters	lb	kg CO2 eq	thou lb
Cut-off Savings/1,000 lb Recycled Resin Compared to Virgin					
Recycled PET	23.6	-50.4	78.5	847	1,880,000
Recycled HDPE	28.6	587	-0.39	605	1,160,000
Recycled PP	28.2	471	18.3	596	140,000

Open-loop Savings/1,000 lb Recycled Resin Compared to Virgin					
Recycled PET	11.8	-25.2	39.3	423	1,880,000
Recycled HDPE	14.3	293	-0.19	302	1,160,000
Recycled PP	14.1	235	9.15	298	140,000

Scaled to US 2015 Recovered Plastic Packaging				
Cut-off Savings				
Recycled PET	4.44E+07	-9.47E+07	1.48E+08	1.59E+09
Recycled HDPE	3.32E+07	6.81E+08	-4.52E+05	7.01E+08
Recycled PP	3.94E+06	6.59E+07	2.56E+06	8.34E+07
Total	**8.15E+07**	**6.52E+08**	**1.50E+08**	**2.38E+09**

Open-loop Savings				
Recycled PET	2.22E+07	-4.74E+07	7.38E+07	7.96E+08
Recycled HDPE	1.66E+07	3.40E+08	-2.26E+05	3.51E+08
Recycled PP	1.97E+06	3.29E+07	1.28E+06	4.17E+07
Total	**4.08E+07**	**3.26E+08**	**7.49E+07**	**1.19E+09**

Equivalencies	Electricity Use per Home per Year	Olympic Swimming Pool	747 Airplane	Personal Vehicle Driven per Year
	million Btu	liters	lb	kg CO2 eq
	41.45	2,500,000	402,300	4,675

	Thousand Households' Annual Electricity Use	Olympic Pools	747 Airplanes	Thousand Vehicles Driven per Year
Cut-off Savings				
Recycled PET	1,071	-38	367	341
Recycled HDPE	801	272	-1.1	150
Recycled PP	95	26	6.4	18
Total	**1,967**	**261**	**372**	**508**

Open-loop Savings				
Recycled PET	536	-19	184	170
Recycled HDPE	401	136	-0.6	75
Recycled PP	48	13	3.2	9
Total	**984**	**130**	**186**	**254**

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*Converted from thousands of short tons in EPA 2015 Sustainable Materials Report, Table 8. Includes recovered bottles and jars, rigid packaging, and other packaging; excludes film packaging.

3.6. CONCLUSIONS

This analysis shows that recycled resins have lower environmental impacts than corresponding virgin resins across the range of results categories analyzed, with few exceptions. Savings are summarized in Table 3-9, with two columns shown for each resin. The first column shows recycled resin results as a percentage of corresponding virgin resin results. The second column in each pair shows the percent reduction in results for recycled resin compared to virgin resin.

Table 3-9. Savings for Recycled Resins Compared to Virgin Resins

	Recycled PET		Recycled HDPE		Recycled PP	
	Recycled % of Virgin	Recycled Resin % Reduction from Virgin	Recycled % of Virgin	Recycled Resin % Reduction from Virgin	Recycled % of Virgin	Recycled Resin % Reduction from Virgin
CUT-OFF						
Total Energy	21%	79%	12%	88%	12%	88%
Water Consumption	104%	-4%	41%	59%	54%	46%
Solid Waste*	42%	58%	101%	-1%	77%	23%
Global Warming	33%	67%	29%	71%	29%	71%
Acidification	30%	70%	53%	47%	42%	58%
Eutrophication	54%	46%	102%	-2%	57%	43%
Smog	25%	75%	63%	37%	50%	50%
OPEN LOOP						
Total Energy	61%	39%	56%	44%	56%	44%
Water Consumption	102%	-2%	71%	29%	77%	23%
Solid Waste*	71%	29%	100%	0%	88%	12%
Global Warming	66%	34%	65%	35%	64%	36%
Acidification	65%	35%	77%	23%	71%	29%
Eutrophication	77%	23%	101%	-1%	79%	21%
Smog	63%	37%	82%	18%	75%	25%

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*Solid waste excluding contaminants removed from incoming material. These contaminants are not caused by recycling and would have been disposed as waste regardless of whether postconsumer plastic recycling takes place.

The table shows that savings for recycled resins are greatest when using the cut-off recycling methodology. For open-loop methodology, the addition of an allocated share of virgin resin burdens increases the results for recycled resins. As a result, open-loop savings compared to virgin resin are lower.