#2 Plastics | Subcommittee Meeting #2 Summary - Plastics July 28, 2021 2PM-4PM

Subcommittee Meeting #2 of the Plastics Subcommittee (#2-Plastics) was convened virtually via Zoom on July 28, 2021 from 2-4 PM, CST. Attendance for #2-Plastics is provided in Table 1 below.

Table 1. #2-Plastics Subcommittee Membership and Attendance

Name	Company	Attended 7/28/21
Harlan Buxbaum	Dee Zee, Inc.	Present
Michele Boney	West Liberty Foods	Present
Troy Willard	Can Shed LLC/ Iowa Recycling Association	Present
Merry Rankin	Iowa State University	Present
Julie Ketchum	Waste Management	Absent
Mick Barry	Mid America Recycling	Present
Scott Vander Sluis	Van's Sanitation and Recycling	Present
Bryce Stalcup	Waste Commission of Scott County	Absent
Jennifer Horner	That's Not Trash, LLC	Present
Joe Bolick	Iowa Waste Reduction Center	Present
Sue Waters	Plastics Recycling of Iowa Falls, Inc.	Absent
Nicole Crain	Iowa Association of Business and Industry	Present
Laurie Rasmus	DNR Internal SMM Team	Present
Amie Davidson	DNR Internal SMM Team	Present
Tom Anderson	DNR Internal SMM Team	Present
Jennifer Wright	DNR Internal SMM Team	Present
Jennifer Reutzel Vaughn	DNR Internal SMM Team	Present
Michelle Leonard	Consultant – SCS Engineers	Present
Christine Collier	Consultant – SCS Engineers	Present
Jeff Phillips	Consultant – SCS Engineers	Present
Karen Luken	Sub-Consultant – EESI*	Present
Aaron Sadow (Guest speaker)	Iowa State University	Present

* Economic Environmental Solutions International

A. Subcommittee #2 - Plastics Summary

The meeting began with the project consulting team reviewing the agenda for this meeting (see Attachment A), the overall objectives of the Sustainable Materials Management (SMM) – Vision for Iowa project, the process and goals of this and the next Subcommittee Meeting, and the materials that were selected for further review during the Subcommittee #1 meeting held June 9, 2021. The identified materials and presented material summaries are listed below:

- Single-Use Water Bottles
  - Bottles are manufactured with petrochemicals and are meant to be disposed of after use.
- Plastic Film and Plastic Bags
  - Thin flexible plastic sheets (e.g., less than 10 millimeters thick) primarily manufactured from polyethylene resin and can be recycled if material is clean and dry.
- Styrofoam - Closed-cell polystyrene, expanded polystyrene foam (EPS)
  - Also known as plastic #6 which is non-biodegradable and has limited recyclability opportunities.

The project consulting team presented a summary of existing plastic diversion efforts occurring in Iowa. These activities include active Iowa State University (ISU) research, various companies using recycled plastics in their manufacturing process (i.e., producing new products, burning plastics for fuel, etc.), and regulations preventing banning the use of certain products (i.e., plastic bags).

Dr. Aaron Sadow, Director, Institute for Cooperative Upcycling of Plastics (iCOUP), Professor of Chemistry, Iowa State University, and Senior Scientist, Ames Laboratory presented a summary of the research his team has been working on in regards to researching new methods for processing plastics for use in new products. Aaron stated that existing reuse and recycling technologies are not sufficient to meet the continued increase in the amounts of plastics produced and used across the globe. In fact, more than 35 million tons of plastics are generated within the United States alone each year with nearly 75% of these tons being landfilled.

Aaron presented an overview of his team's research attempting to upcycle the waste plastics into a variety of chemical compounds allowing those chemicals to then be separated and used to manufacture a variety of other products. These other products could range from low value products such as consumer goods (i.e., plastic bags, containers, etc.) to high value products such as synthetic machine oil. Processing waste plastics into new products is difficult due to the contamination of the material (i.e., mixed plastic types in one product, adhesives for labels, mixed with non-plastic waste, etc.) and the costs associated with removing these contaminants. Aaron hopes that his team's research identifies successful methods and technologies that can be used by manufacturers to help increase the diversion of plastics from being landfilled.

Aaron's presentation is included in Attachment B.

A question was asked concerning if pyrolysis to convert plastics to fuel was a viable solution. Aaron stated that while this technology exists, it isn't a long-term solution and that there is likely a better alternative to making valued products from waste plastics.

The project consulting team then presented several summaries of life cycle analysis (LCA) reports that have been done related to the plastic materials identified during Subcommittee Meeting #1. Presented LCAs covered the following primary materials:

- Water Bottles
- Plastic Bags
- Packaging

- Plastic Film Waste
- Production of Postconsumer Recycled Resins (PET, HDPE, PP)
- Alternatives to EPS Single-Use Takeout Containers
- Disposable EPS Plates and Paper Plates; Egg Packaging EPS; and Recycled Paper

The summary slides that were presented are located in Attachment B. The LCAs reviewed are located in Attachment C with a brief summary of each below.

Water Bottles – LCA:

A variety of LCAs were reviewed and they compared the environmental impacts of the following:

- Drinking water from the tap;
- Drinking water from a 5-Gallon reusable plastic container; and
- Drinking water from a single-use bottle.

The studies indicated that drinking water from the tap had the lowest environmental impact compared to the others. The environmental impacts of recycling plastic containers were moderate and disposal of the plastics had small environmental impacts. The greatest environmental impacts come from the manufacturing and transportation of the plastic containers themselves. In fact, the studies showed that if the plastic containers were manufactured and/or transported outside of the region of consumption, the negative environmental impacts were three-times as high.

Plastic Bags – LCA:

Many LCA studies have been performed on single use plastic bags. A summary review of these reports was presented and focused on reusable bags, single use bags (paper and plastic), and LDPE bags. One of the factors that the studies considered when evaluating the LCA for bags was how many times the bag was likely to be used. Primarily, the more times a bag could be used due to its manufactured qualities (i.e., thicker plastic material to help prevent breaking or taring), the less negative environmental impact the bag had on the environment. Therefore, reusable plastic bags (i.e., LDPE bags) had less of a negative environmental impact than single use bags (i.e., paper, plastic, etc.).

When just comparing the environmental impacts of the single use bags, single use plastic bags have less of a negative impact on the environment than single use paper bags or single use biodegradable bags in all stated categories except for litter generation.

Packaging – LCA:

Packaging LCAs that have been performed focused on determining whether the packaging material attributes of recyclability, recycled content, compostability, and biobased, commonly considered to be environmentally beneficial correlate with lower net environmental impacts across the full life cycle of the packaging. The LCAs identified a number of instances where material attributes do not correlate with environmental benefits for packaging. Rather, other characteristics such as material choice or mass of the packaging can have higher influence in determining life cycle impacts.

Plastic Film Waste – LCA:

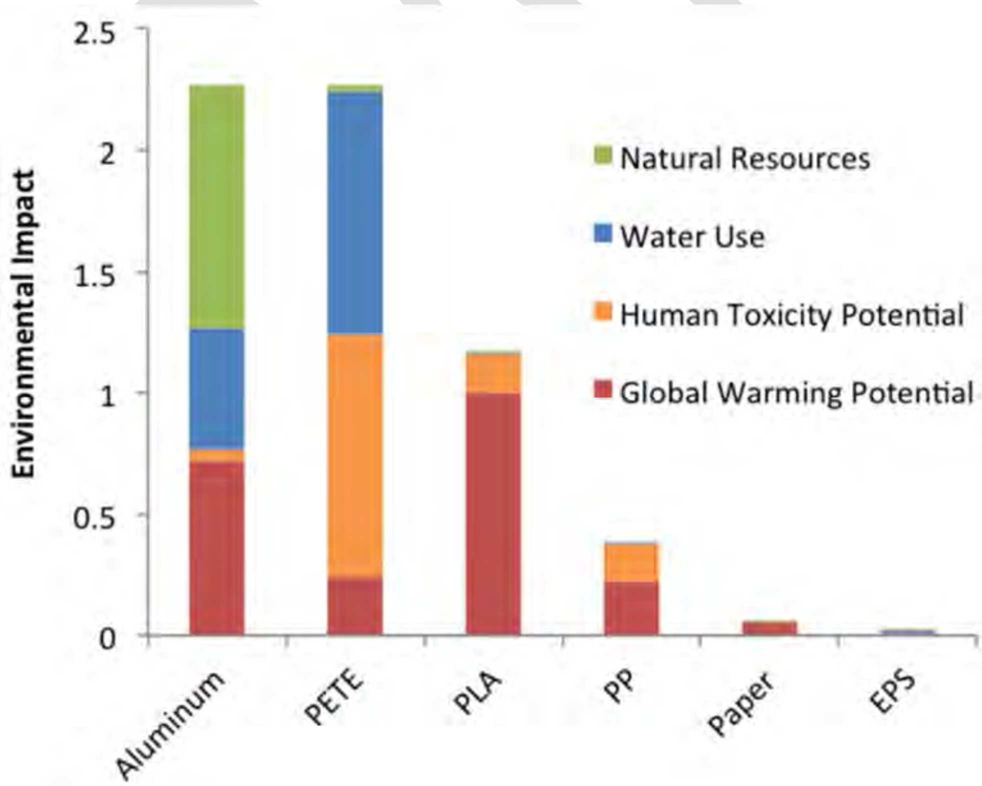
According to the reviewed LCAs, there is an environmental advantage for recycling plastic film waste rather than landfill disposal or incineration. Recycling appears to be particularly favorable when the plastic film waste is recovered from mixed waste rather than from recyclable waste. Consumer drop-off programs for plastic film have the highest environmental impacts among collection scenarios evaluated for plastic film waste.

Production of Postconsumer Recycled Resins (PET, HDPE, PP) – LCA:

Reviewed LCAs worked to quantify energy and water use, global warming potential, acidification, eutrophication, smog formation, and solid waste. The LCAs also included methods for collection, sorting, and reprocessing of plastic resins. The conclusions were that recycled resins have lower impacts than virgin resins in most if not all categories evaluated.

Alternatives to EPS Single-Use Takeout Containers – LCA:

LCAs evaluated the end of life management of five container types (PET, PP, corn-based plyactic, paper, and aluminum) for their impacts on global warming potential, human toxicity potential, water use, and natural resource use. The LCAs then weighted the results as level of environmental impacts which are shown in the figure below. EPS had the lowest environmental impact and paper had the second lowest impact. Aluminum and PET had the highest environmental impacts according to the LCAs.



Disposable EPS Plates and Paper Plates; Egg Packaging EPS and Recycled Paper – LCA:

LCAs that covered disposal EPS plates compared to paper plates, egg packaging EPS, and recycled paper were reviewed and the summary results are listed below.

EPS Plates vs. Paper Plates - LCA:

The LCA results stated that EPS plates have less of an environmental impact than paper plates primarily due to their lighter weight and use of less material. The LCAs indicated that EPS plates had lower environmental impacts for: energy demand, water use, acidification, eutrophication, and waste disposal.

Egg Packaging EPS vs. Recycled Paper – LCA:

The LCAs indicated that the EPS packaging contributes more to acidification potential, winter and summer smog, while paper packaging contributed more to heavy metal and carcinogenic substances impact. The LCA results stated that recycled paper egg packaging have less environmental impact than EPS packaging.

STRATEGIES

The project consulting team presented strategies that other entities have developed to encourage reduction of plastic waste generation and to divert the material from being landfilled. Presented example strategies are summarized below.

Post-Consumer Recycled Content:

California, New Jersey, and Washington have established regulations establishing a minimum percentage content of post-consumer recycled content be used in the manufacturing of targeted products. Targeted products range from plastic bags to beverage containers.

Polystyrene Container Bans:

Colorado, Maine, Maryland, New York, Vermont, and Virginia have passed regulations banning the use of polystyrene containers.

Extended Producer Responsibility (EPR):

Extended producer responsibility (EPR) regulations places the responsibility for the treatment and disposal of targeted products and/or materials on the producers and manufacturers of these items. EPR programs can also assign treatment and disposal responsibilities on retailers. EPR Programs are typically funded from fees assessed to consumers at the time of purchase of the product covered under the EPR. These funds are then used to support product treatment and disposal programs performed by the producer, manufacturer, and/or retailer. Collected funds may also be used to reimburse a third-party entity (i.e., local government entity, etc.) that provides these services.

The states of Maine and Oregon have passed EPR regulations. The states of California, Hawaii, Maryland, Massachusetts, and New York have proposed EPR similar regulations that are in various stages of consideration.

Plastic Bag Bans:

Eleven states have passed various regulations banning the distribution of single-use plastic bags. Some of these regulations ban the use of the plastic bags completely, others have an added tax on plastic bags, and some ban plastic bags based on the bag's thickness.

Eleven states (including Iowa) have passed pre-emption regulations preventing the banning of the use of plastic bags.

Environmental Tax Credits and Impact Taxes:

Three tax based examples were presented. They are summarized below:

- R&D Tax Credit
  - Allows a percentage tax credit for eligible spending for new and improved products and processes. This tax credit is used by Iowa's renewable energy and alternative fuels industries.
- Emissions Tax
  - Imposes a tax based on the emissions of the entity. There are currently no emission tax systems approved in the US.
- Cap and Trade
  - Establishes a maximum emissions rate for an entity (i.e., cap). If an entity exceeds this emission rate, they must purchase credits from other entities (or established emissions trading markets) that have not exceeded their maximum emissions rate. These purchased credits off-set the exceeded emissions rate.

BARRIERS and CHALLENGES

Subcommittee participants were then asked what barriers they see as needing to overcome in order to improve how the following materials identified during the Subcommittee Meeting #1 are managed in Iowa:

- Single-Use Water Bottles
- Plastics Film and Plastic Bags
- Styrofoam

The following are summaries of discussions or statements that were made by Subcommittee members concerning the following main topics:

Single-Use Water Bottles:

- Adding water bottles to the Bottle Bill has been discussed for many years. This addition would require legislation modifications and it's a concern that the Bottle Bill may be repealed.
- Iowa manufacturers, financial institutions, and distributors have expressed an aversion to adding more materials to the Bottle Bill.
- Focusing on policies that reduce and reuse plastic bottles would be better than adding them to the Bottle Bill.

- Avoiding the production of the water bottle in the first place should be a priority as that would have the largest positive environmental impact.
- People use single use plastic bottles because it was made for their convenience. If you are going to manufacture something that is going to become a problem – the producer should have some responsibility for the management of that product.
- Any non-carbonated container should be added to the Bottle Bill – not just water bottles. We are trying to achieve a higher recovery rate and keep litter down.
- To help redemption centers become financially viable, increasing the number of containers they receive for processing will increase their potential revenue. That said, it may not be enough to just increase their volumes, it would likely require an increase in the processing fee (currently $0.01/ container).
- Plastic water bottles should be added to the Bottle Bill.
- If grocers were no longer required to accept deposit containers in the store, they would likely support (or at least not obstruct) the expansion of the Bottle Bill to include other containers.
- Companies are testing the production of bottles manufactured with 100% recycled plastics materials.
- Removing plastic bottles from the recyclable stream improves the sorting efficiencies at material recovery facilities (MRFs) and decreases the contamination rates of the processed paper. While these plastics are a source of revenue for MRFs, the costs associated with managing them through the sorting system are more than these revenues.
- Iowa has some of the lowest recyclable processing fees in the United States primarily due to the fact that the Bottle Bill limits the amount of plastic containers in the recycling stream.

Plastic Film and Plastic Bags:

- Our company has hired a packaging engineer to evaluate how they can reduce the amount of materials used in their packaging.
- A large retailer is requiring recyclable film plastic to be used to package meat products sold in their stores. The packaging must also include labeling informing the consumer that the plastic film is recyclable. While using recyclable plastic film is possible, the concern is how consumers will attempt to recycle this material. If they attempt to recycle this material in their regular recycling programs, this may cause contamination of other recyclable materials and cause operational issues at MRFs.
- Retailers can make an impact by charging customers $0.10/single use plastic bag. This fee discourages excessive use.

Single-Use Water Bottles, Plastic Film and Plastic Bags, and Styrofoam:

- Establishing emission or other limitations (i.e., cap and trade and tax incentive systems) are concerning to businesses. Businesses are already working to reduce the quantity of their waste streams and do not want government regulations interfering with their efforts.

- Manufacturers and producers make products that consumers demand. Therefore, if consumers no longer demanded these materials, they would no longer be made.
- Establishing state-wide policies would be preferred over individual county policies. Policies can vary greatly from county to county and cause confusion and frustration for businesses attempting to locate in or perform services in Iowa.
- Iowa has initiated a statewide recycling education campaign to help improve consumer awareness of recycling programs and increase program participation. The hope is that this program will help decrease contamination rates.
- Increasing demand for use of recycled plastics in manufactured products is good, but we need to ensure they can source these materials in Iowa. Doing so may help incentive these types of businesses to locate in Iowa.

B. Research Request List

Through the discussions and in follow up discussions, various topics have been identified for further research. These are provided below.

- Research large retail entities (i.e., Walmart, Target, etc.) to understand what practices they implement to reduce plastics in their products and in their stores? Are large retailer practices positively, and possible even negatively, impacting existing recycling systems?
- Contact Iowa Economic Development Authority to determine if there are bottle manufacturers in Iowa that manufacture pop bottles from 100% recycled plastic resins for Canada markets.

C. Other Notes

Other items of note from the #2 - Plastics meeting are as follows:

- Next Plastics subcommittee meeting date and time is:
    - September 1, 2021, 2 PM-4PM CST
- Second Stakeholder Meeting will be held on September 30, 2021. Subcommittee members in addition to other interested parties are invited and encouraged to attend.

Attachments:

Attachment A: Agenda

Attachment B: PowerPoint Presentations

Attachment C: Additional Information

Attachment A
Agenda

Subcommittee Meeting #2 - Plastics

July 28, 2021

2:00PM – 4:00PM (CST)

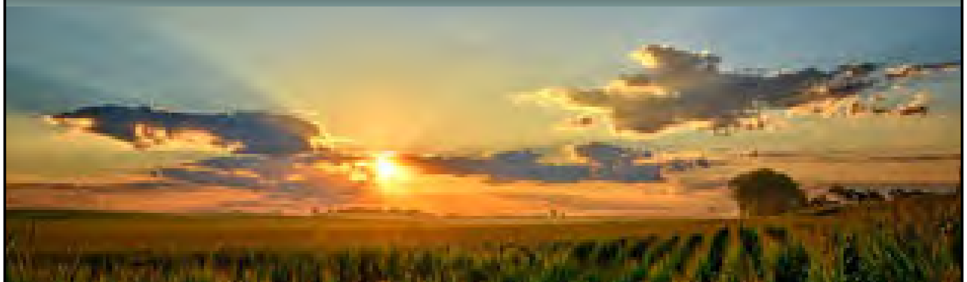
Virtual Meeting

1. Subcommittee Meeting Purpose and Goals
2. Material Types Discussion
    a. Single Use Water Bottles
    b. Plastic Film and Bags
    c. Polystyrene (Styrofoam)
3. Existing Activities in Iowa
4. LCAs, WARM Model, Other Research
5. Strategies From Around the US and Elsewhere
6. Next Steps
    a. Begin Strategy Prioritization
    b. Future Meetings Dates and Logistics

Attachment B
PowerPoint Presentations

IOWA DNR | PHASE II SMM VISION FOR IOWA

SCS ENGINEERS



Plastics Subcommittee Meeting #2
July 28, 2021

IOWA DNR | PHASE II SMM VISION FOR IOWA

SCS ENGINEERS

Agenda

- **Subcommittee Meeting Purpose and Goals**
- **Material Types Discussion**
  - **Single Use Water Bottles**
  - **Plastic Film and Bags**
  - **Polystyrene (Styrofoam)**
- Existing Activities in Iowa
- LCAs other research
- Strategies from around the US and elsewhere
- **Next Steps**
  - Begin to prioritize strategies
  - Future meeting dates and logistics

Goal

Establish a clear direction for implementing an SMM system with immediate, medium and long-term strategies

Process

Select specific material types within each category → Define specific strategies
- Legislation
- Policies
- Programs
- Infrastructure
- Funding mechanism

→ Identify implementation timeline, responsible party, and performance metrics

Material Types Selected

Single-Use PET Water Bottles

Plastic Film/Bags

Polystyrene (Styrofoam)

Single-Use PET Water Bottles

- **single-use plastics** are goods that are made primarily from fossil fuel–based chemicals (petrochemicals) and are meant to be disposed of right after **use**—often, in mere minutes

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS

Plastic Film/Bags

- Plastic bags are made out of “film,” or thin flexible sheets of plastic
- Plastic film is typically defined as any plastic less than 10 mil thick.
- The majority of plastic films are made from polyethylene resin and are recyclable if the material is clean and dry and facilities are able to process it

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS

Expanded Polystyrene Foam

- Styrofoam is a Dow Chemical Co. trademark
- AKA: Closed-cell extruded polystyrene, Expanded Polystyrene Foam (EPS)
- Plastic #6
- Non-biodegradable
- Limited Recyclability

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS

Existing Activities in Iowa

Research and Development	Recycling Companies	Laws and Regulations

• Iowa State University
  • DOE Grants
  • Center for Bioplastics and Biocomposites
  • Institute for Cooperative Upcycling of Plastics
• Iowa Corn Promotion Board Patent for MEG
	• Quincy Recycling
	• Plastics Recycling of Iowa Falls
	• Power Plastic Recycling
	• Mid America Recycling
	• Recycling Inc.
	• Cedar Falls
	• Atlas Molded Products
	• Foam Fabricators
		• No Plastic Bag Bans
		• Advanced Plastic Recycling

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS

Research

LCA:
Water Bottles

- Compared environmental impacts of:
  - Drinking water from the tap
  - 5-gallon reusable
  - Single-use bottles
- Recycling has moderate environmental benefits
- Disposal impacts are small
- Disposal of biodegradable bottles creates GHGs
  - 888 equivalent tons of CO^2 in Iowa
- Greatest impacts from making and transporting bottles
- Drinking water from the tap typically has substantially lower impacts

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS

LCA: Plastic Bags

- Reusable bags have lower environmental impacts than single-use bags, depending on usage.
- Reusable LDPE bags have lower climate impacts than conventional single-use plastic bags, if used 5-10 times more than the single-use bag
- Single-use plastic bags rank better than single-use paper bags and biodegradable bags
- Paper bags can be better for the climate than single-use plastic bags
- Biodegradable bags have lower contribution to GHG emissions than paper bags
- Biodegradable bag has no significant environmental benefits compared to conventional SUPBs

LCA: Packaging

- Analyzed correlation of recyclability, recycled content, compostability, and bio-based attributes to lower environmental impacts
- Results: material attributes do not correlate with environmental benefits for packaging
- Material choice or mass of the packaging can have higher influence in determining life cycle impacts

LCA: Plastic Film Waste End-of-Life Treatment

- Recycling films shows greater environmental benefit than landfilling and incineration
- Greatest benefit when recovered from mixed waste
- Consumer drop-off has the highest environmental impacts among collection scenarios
- Mass fraction of plastic film is the key parameter to improve environmental benefit
- Recycling rate, utilization rate, and WTE conversion rate are important parameters
- Cooperation from multi-stakeholder is required to increase recycling

LCA: Production of Postconsumer Recycled Resins - PET, HDPE, PP

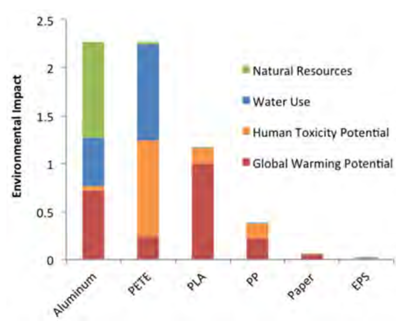
- Quantified energy and water use, global warming potential, acidification, eutrophication, smog formation, and solid waste
- Included collection, sorting, and reprocessing
- Identified relative environmental impacts of recycled and virgin plastic resins
- Conclusions:
  - Recycled resins have lower impacts than virgin resins in most if not all categories

LCA: Alternatives to EPS Single-Use Takeout Containers

- Analysis of five container types:
  - PET
  - Polypropylene (PP)
  - Corn-based Polylactic Acid (PLA)
  - Paper
  - Aluminum
- Quantified impacts:
  - Global warming potential (GWP)
  - Human Toxicity Potential (HTP)
  - Water Use
  - Natural Resource Use

Results

- Scenarios relate to container's end of life
- 67% composting/ recycling; 34% landfilling
- EPS had lowest environmental impact due to low GWP and HTP
- Paper second lowest
- Aluminum and PET highest



LCA: Disposable EPS plates and Paper Plates; Egg packaging EPS and Recycled Paper

PLATES

- Results more favorable for foam plate due to lighter weight/less material
- Lower environmental impacts for:
  - Energy demand
  - Solid waste
  - Water use
  - Acidification
  - Eutrophication
- Foam plate has higher non-renewable energy demand
- Foam plate has lower GWP

EGG CARTONS

- PS packages contribute more to acidification potential, smog
- Recycled Paper packages contribute more heavy metal and carcinogenic substances impact
- Overall, paper have less environmental impacts than PS

BREAK (10 Minutes)

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS 20

Strategies

Post-Consumer Recycled Content

- California
- New Jersey
- Washington

Establishes minimum post-consumer recycled plastic use in containers, bags, other household products

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS

22

Polystyrene Container Bans

- Colorado (2024)
- Maine
- Maryland
- New York (2022)
- Vermont
- Virginia (2023; 2025)

Extended Producer Responsibility

Places responsibility for treatment and disposal of products on producers, manufacturers, and retailers

Producer EPR vs. Reimbursement EPR

Extended Producer Responsibility

- **Maine** first state to sign EPR for plastics and packaging materials
- **Oregon** legislature passed EPR for plastic packaging, paper, and food service ware

Proposed Bills
- California
- Hawaii
- Maryland
- Massachusetts
- New York

IOWA DNR | PHASE II SMM VISION FOR IOWA SCS ENGINEERS

Plastic Bag Bans

STATES WITH BANS
- California
- Colorado
- Connecticut
- Delaware
- Hawaii
- Maine
- New Jersey
- New York
- Oregon
- Vermont
- Washington*

STATES WITH PRE-EMPTIONS
- Arizona
- Idaho
- Iowa
- Florida
- Indiana
- Mississippi
- Missouri
- North Dakota
- Oklahoma
- Tennessee
- Wisconsin

Environmental Tax Credits and Impact Taxes

- R&D Tax Credit
- Emissions Tax
- Cap and Trade

Infrastructure/Policy/ Funding Gaps in Iowa

KEY QUESTIONS

- Would Iowa consider adding single-use water bottles to the bottle bill?
- Would Iowa re-consider single-use bag ban?
- Would Iowa consider any plastic bans?
- What incentives can be provided for industries to facilitate plastic recycling?
- What measures can be implemented to reduce plastic waste generation?

BREAK (10 Minutes)

Catalytic Recycling and Upcycling of Polyolefin Waste

Aaron D. Sadow

28 July 2021, Plastics Subcommittee

Acknowledgements

U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Basic Energy Science
Chemical Sciences, Geosciences, and Biosciences Division, Catalysis Science Program

Argonne National Laboratory

M. Delferro
B. Lee
T. Li
G. Celik
R. Kennedy
R. Hackler
M. Ferrandon

Ames Laboratory
Creating Materials & Energy Solutions
U.S. Department of Energy

F. Perras
W. Huang
A. Sadow
A. Paterson
S. Chen
S. Patnaik
M. Pruski
U. Kanbur
A. Tennakoon
X. Wu
M. Esveld
Y. Pei

Cornell University

G. Coates
A. LaPointe
A. Kocen

Northwestern University

K. Poepplemeier
E. Luijten
I. Peczak
M. Meirow

UC Santa Barbara

S. Scott
M. Abu-Omar
F. Zhang
J. Sun
A. Lee
D. Zeng

University of South Carolina

A. Heyden
S. Ammal
K-E. You

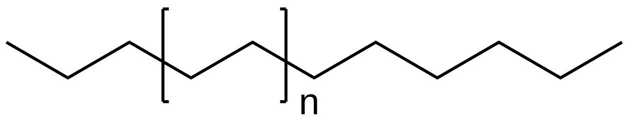
University of Illinois Urbana-Champaign

B. Peters
R. Yappert

The project was initiated with support for the Catalysis for Polymer Upcycling FWP (Ames Lab and ANL) and completed in the Institute for Cooperative Upcycling of Plastics (iCOUP), an Energy Frontier Research Center funded by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES) through the Ames Laboratory under its Contract No. DE-AC02-07CH11358 and Argonne National Lab under its Contract No. DE-AC-02-06CH11357.

Energy and Environmental Issues of the Plastic Waste Crisis

- **Discarded plastics are an energy problem**
  - Production consumes an annual equivalent of 6-8% worldwide oil and LNG
- **Discarded plastics are an environmental problem**
  - Polymers generate 300 M tons of municipal solid waste (MSW) worldwide (2015)
  - Polyethylene (PE), polypropylene (PP), and polystyrene (PS) make up ~55% of this waste
  - US generates ca 35 M tons of plastic MSW, with 75% landfilled
  - 19-23 M tons are estimated to leak into oceans each year (2016), degrade into microplastics, and enter the food chain
  - Environmentally-aged PE generate methane and ethylene greenhouse gases
- **Current methods and technologies brought to bear are necessary, yet insufficient to keep up with growth of waste!**



high density (HD)PE

Hopewell, J.; Dvorak, R.; Kosior, E., Plastics recycling: challenges and opportunities. *Philos. Trans. R. Soc. London, Ser. B* **2009**, *364*, 2115. Geyer, R.; Jambeck, J. R.; Law, K. L., Production, use, and fate of all plastics ever made. *Science Advances* **2017**, *3*. doi:10.1126/sciadv.1700782. Borrelle, S. B. et. al Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science* **2020**, *369*, 1515.

Economic Challenges and Opportunities of the Plastic Waste Crisis

- **Discarded plastics are an economic problem**
  - Recycling is energetically and economically limited
  - Most plastics are designed for single-use applications (packaging)
  - Physical properties often degrade in recycling or reprocessing
  - Commodity plastics are precisely constructed for their applications
  - More expensive to collect, purify, and melt-process to recycled materials than to manufacture (many) new plastics from petrochemicals
- **Instead, processing should add value**
  - Energy value of current PE + PP + PS waste ≈ 1.3 B barrels of oil worldwide
  - US consumes ~7.3 B barrels/year
- **Conventional Approaches**
  - Mechanical recycling (mainly PET and HDPE)
  - Gasification
  - Pyrolysis (to fuel)
  - Depolymerization (PET methanolysis or hydrolysis, PS)
  - Extraction, filtration, reprecipitation (PS and *i*PP)

Rahimi, A.; García, J. M., Chemical Recycling of Waste Plastics for New Materials Production. *Nat. Rev. Chem*. **2017**, *1*, 0046. doi:10.1038/s41570-017-0046. https://www.eia.gov/totalenergy/ See *C&EN News*, Chemical Recycling 11 Oct 2020

Reduce, Reuse, Recycle. Add **Recoup**

Chemical upcycling, the conversion of used materials into higher value products, could provide a second life for plastics

catalyst
[O]

fatty alcohols
emulsifiers

biodegradable

catalyst
CO_2

fatty acids
surfactants

cyclic alkanes
high value commodity

"natural" HDPE in milk jugs can be collected and sold for ~$750-$850/ton (2019), then melted and recycled

chemical recycling

small alkenes
(ethylene – butene)

functionalized plastics
new materials

alkanes
lubricants and waxes

polyolefins
high quality plastics

recyclable: https://cswd.net/general-topics/keep-calm-and-recycle-on-part-1-the-life-of-a-milk-jug/

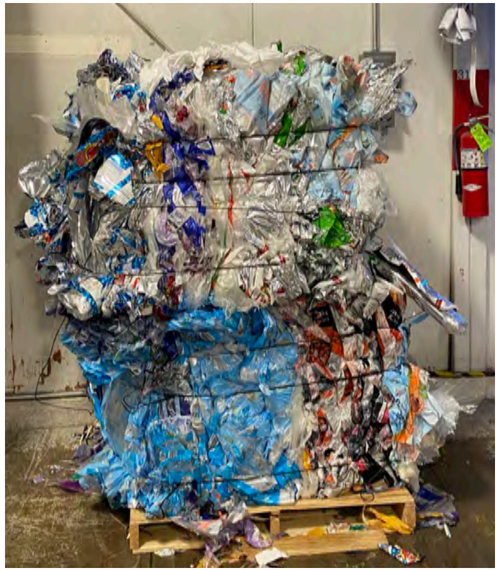
iCOUP

U.S. DEPARTMENT OF ENERGY | Office of Science

Reduce, Reuse, Recycle. Add **Recoup**

Chemical upcycling, the conversion of used materials into higher value products, could provide a second life for plastics

post-industrial plastic



catalyst [O] → fatty alcohols
emulsifiers

biodegradable

catalyst, CO_2 → fatty acids
surfactants

→ small alkenes (ethylene – butene)

chemical recycling

→ polyolefins
high quality plastics

→ cyclic alkanes
high value commodity

"natural" HDPE in milk jugs can be collected and sold for ~$750-$850/ton (2019), then melted and recycled

→ functionalized plastics
new materials

→ alkanes
lubricants and waxes

recyclable: https://cswd.net/general-topics/keep-calm-and-recycle-on-part-1-the-life-of-a-milk-jug/

Reduce, Reuse, Recycle. Add **Recoup**

Chemical upcycling, the conversion of used materials into higher value products, could provide a second life for plastics

post-industrial plastic

catalyst [O] → fatty alcohols
emulsifiers

biodegradable

catalyst CO_2 → fatty acids
surfactants

→ small alkenes (ethylene – butene)

chemical recycling

→ polyolefins
high quality plastics

← cyclic alkanes
high value commodity

“natural” HDPE in milk jugs can be collected and sold for ~$750-$850/ton (2019), then melted and recycled

→ functionalized plastics
new materials

→ alkanes
lubricants and waxes

recyclable: https://cswd.net/general-topics/keep-calm-and-recycle-on-part-1-the-life-of-a-milk-jug/

iCOUP

U.S. DEPARTMENT OF ENERGY | Office of Science

Project Goals for Process Development of Lubricating Oils from Upcycled Plastics (LOUPS)

Develop a modular, low-temperature (< 300 °C) and low pressure (15 bar) continuous process for the integrated catalytic conversion and distillation of single-use waste polyolefin films and laminates of high-density polyethylene (HDPE), low density (LD)PE, linear low density (LLD)PE, and isotactic polypropylene (*i*PP) into higher value, high performance LOUPs.

Polyolefin Waste → (conversion; continuous hydrogenolysis + purification) → LOUPs → (tribology; lubricant property evaluation and blending) → (process assessment; TEA, LCA) → Validated Process for Upcycling of Polyolefin Plastics Waste

Iowa State University · Chevron Phillips Chemical — Performance by design. Caring by choice.™ · Chemstations™ · Texas A&M University · Argonne National Laboratory

Value Proposition

Annual Polyolefin Waste

~150 M tons

~$60 B lost

equivalent to discarding 1.2 B barrels of oil

conversion

Polyolefin Waste → Lubricating Oils

HDPE films from grocery bags

LLDPE, HDPE, PP or mixed laminates wastes for food packaging

plastic MSW

"LOUPs'

High performance lubricants, hydrolytic fluids, heat transfer fluids, greases

Annual Lubricant Market

~40 M tons

~$160 B

Can LOUPs provide equivalent or better performance with lower manufacturing costs compared to conventional lubricating oils?

Iowa State University | Chevron Phillips Chemical — Performance by design. Caring by choice.™ | Chemstations™ | Texas A&M University | Argonne National Laboratory

Thanks!

Questions?

Attachment C
Additional Information

Life Cycle Analysis Information for Plastics – Iowa Waste Reduction Center (IWRC) Research Results and Sources:

Plastic Bags

https://plastics.americanchemistry.com/Life-Cycle-Assessment-for-Three-Types-of-Grocery-Bags.pdf

These study results confirm that the standard polyethylene grocery bag has significantly lower environmental impacts than a 30% recycled content paper bag. This supports conclusions drawn from a number of other studies looking at similar systems.14, 15, 16 In addition, this report also shows that the typical polyethylene grocery bag has fewer environmental impacts than a compostable plastic grocery bag made from a blend of EcoFlex (BASF), polylactic acid, and calcium carbonate, when compared on a 1:1 basis, as well as when the number of bags is adjusted for carrying capacity so that the comparison is 1.5:1. Surprisingly, the trend is the same for most of the individual categories of environmental impacts. No one category showed environmental impacts lower for either the compostable plastic bag or the paper bag.

In the case of reducing dependence on overall energy, it is clear (see Table 34) that neither the life cycle of a compostable bag nor paper bag provides a reduction in overall energy use. The standard polyethylene plastic grocery bag uses between 1.8 and 3.4 times less energy than the compostable and paper bag systems, respectively.

The results of this study also show that the standard polyethylene single-use plastic grocery bag's contribution to the solid waste stream is far lower than either the paper bag system or the compostable bag system. This is not surprising considering both the compostable bag and paper bag systems require more material per bag. The increase in solid wastes has become an important global issue as populations multiply and developing countries become wealthier, consuming more material goods. Currently, more land is being devoted to the disposing of solid wastes, and the lack of proper containment in solid waste facilities is causing problems in terms of soil contamination and water pollution.

Increased recycling rates for plastic bags, better bagging techniques at retail, and secondary uses of plastic grocery bags such as waste disposal could all further reduce the environmental impacts of plastic grocery bags. In addition, getting consumers to change their behavior so that plastic bags are kept out of the litter stream would appear to be more productive in reducing the overall environmental impact of plastic bags including litter.

This study supports the conclusion that the standard polyethylene grocery bag has significantly lower environmental impacts than a 30% recycled content paper bag and a compostable plastic bag. An LCA report and its findings can be used to demonstrate that an environmental impact analysis needs to take into account the entire picture, and when dealing with a product that is likely to be replaced by another, the trade-offs in the environmental impact of the replaced alternative should also be given a critical analysis.

Styrofoam

https://flaglerlive.com/wp-content/uploads/Styrofoam.pdf

Eco-Foam® • Made from corn (starch). • Creates no static-electricity (as does Styrofoam) and is much better for protecting very delicate electronics, like microchips. • You can put it in your backyard compost, i.e . it's 100% biodegradable (as long as it's not packed down in a landfill). • Comes in nearly everything from packing "peanuts" to molded Eco-foam and insulation, plates, cups, and utensils (they make biodegradable trash bags, too).

Natural Insulation • M.I.T. developed straw insulation that costs half as much as Styrofoam insulation, is non-toxic and is biodegradable. • Made with an easily renewable, natural resource. • Straw plus a sticky adhesive agent and compression = eco-friendly insulation. • Predicted to be great for building in developing countries because of low cost and very easy to manufacture.

PET

https://plasticsrecycling.org/images/library/2018-APR-LCI-report.pdf

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.

Film

https://www.sciencedirect.com/science/article/pii/S0959652618322674

The life cycle assessment conducted in this study indicates there is an environmental advantage for recycling plastic film waste rather than consigning it to landfill disposal or incineration. Recycling appears to be particularly favorable when the plastic film waste is recovered from mixed waste rather than from recyclable waste, on account of the higher mass fraction of plastic films in mixed waste, despite the lower recycle rate. This is not to suggest that recycling of plastic films from recyclable waste be discouraged. Rather, waste management. Instead, policies should encourage consumers to separate plastic films from mixed waste so as to increase the recoverable fraction of plastic films in recyclable waste. This is also confirmed by the sensitivity analyses that increasing the mass fraction of films in waste will significantly improve the environmental benefit of recycling.

Besides mass fraction of films in waste, sensitivity analysis also identified the recycling rate at the MRF, utilization rate, and incinerator waste-to-energy ratio as key parameters governing the life cycle environmental impacts of plastic film end-of-life treatments. More investigation is needed to collect data to better characterize MRF recycling, utilization, and waste incineration processes. Technology development should consider improvements to MRF recycling, utilization, and waste incineration efficiency, as the analysis presented herein suggests that such efforts will deliver greater environmental rewards than shortening plastic film waste collection route distances or reducing energy consumption at MRF.

Consumer drop-off is found to have the highest environmental impacts because more trips are required to collect the same amount of waste compared to trucks. Therefore, on-purpose drop-offs are not encouraged. Effective policy design should consider how to make curbside collection sites available and convenient for more residents.

Since significant benefits are shown from recycling plastic films, additional resources should be dedicated to improving the overall recycling rate. There are still technical barriers for film recycling. Tailored equipment is needed for film recycling. However, to make the equipment investment economically variable, sufficient volume of plastic film waste is required. This requires the cooperation of multiple stakeholders. First, packaging designers should design clear and easy to understand labels indicating recyclability and provide necessary instructions, such as to keep the film dry and clean and to recycle it to specific collection sites. Second, communities should collaborate with industry experts to educate residents for plastic film recycling and encourage their participation. In addition, before the volume of recycled films is sufficient, public funding is required to make the recycling profitable.

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

SUBMITTED TO:

The Association of Plastic Recyclers

SUBMITTED BY:

Franklin Associates, A Division of Eastern Research Group (ERG)

December 2018

Franklin Associates
A Division of ERG

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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.

---

[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

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

[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

[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.

---

[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

	Per 1000 lb		Per 1 kg	
Bale to Pellet				
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

(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.

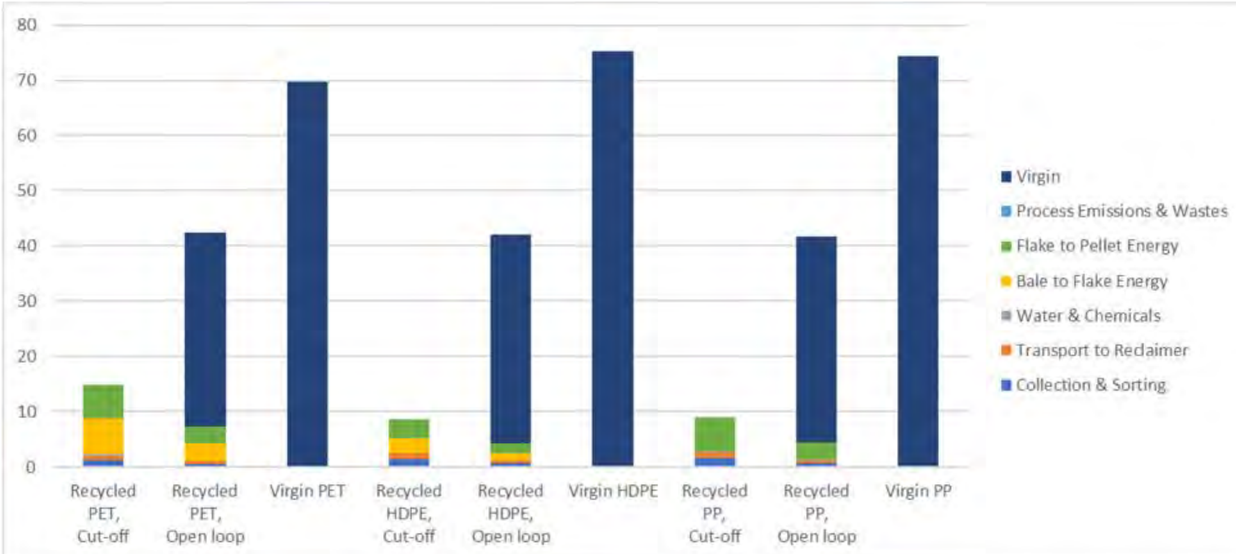


Figure 3-1. Total Energy Results for Recycled and Virgin Resins (MJ/kg)

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.

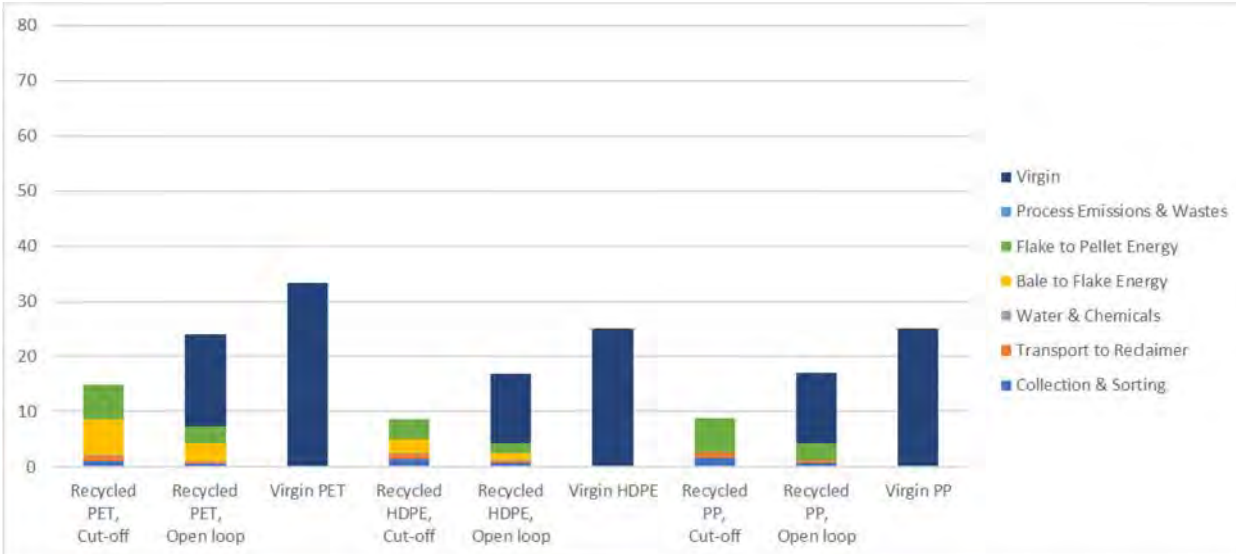


Figure 3-2. Process and Transportation Energy for Recycled and Virgin Resins Excluding Feedstock Energy (MJ/kg)

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.

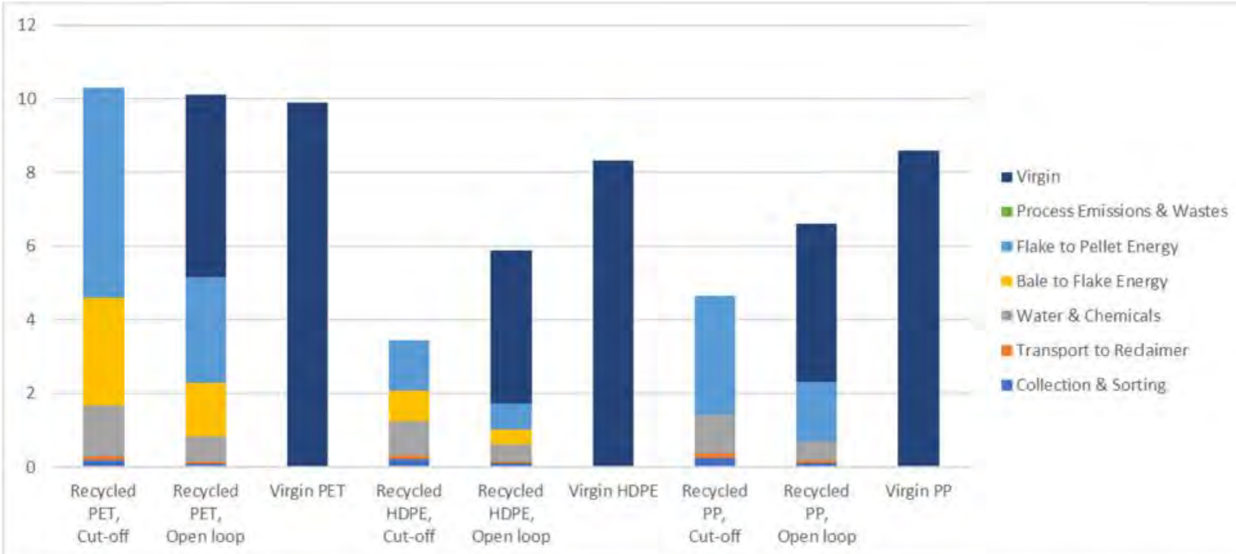


Figure 3-3. Water Consumption Results for Recycled and Virgin Resins (liters water/kg resin)

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.

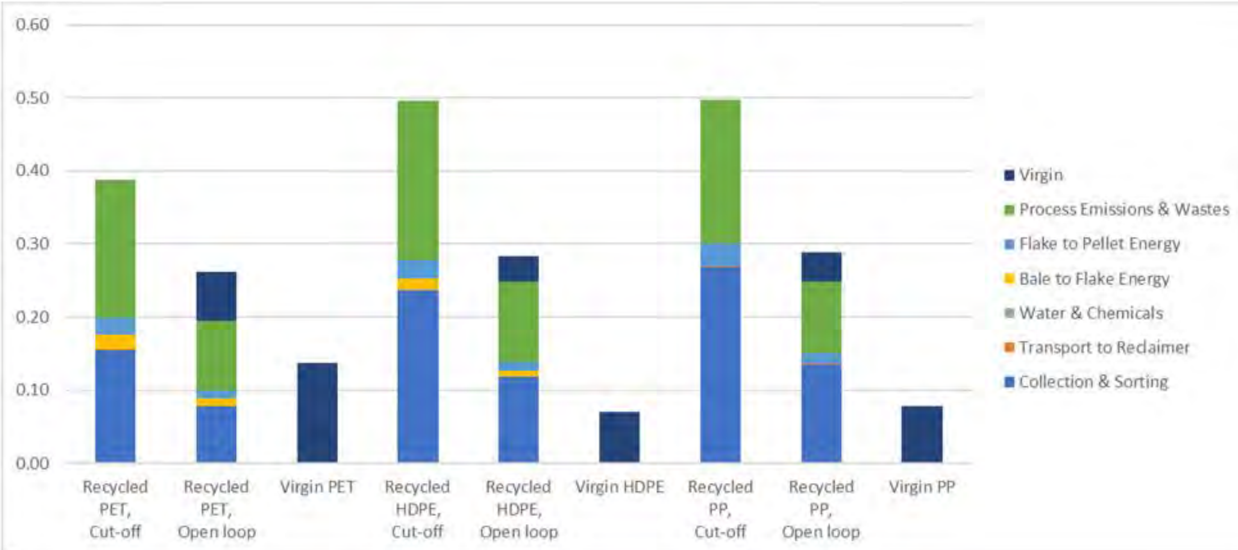


Figure 3-4. Solid Waste Results for Recycled and Virgin Resins, Including Contaminants in Incoming Material (kg waste/kg resin)

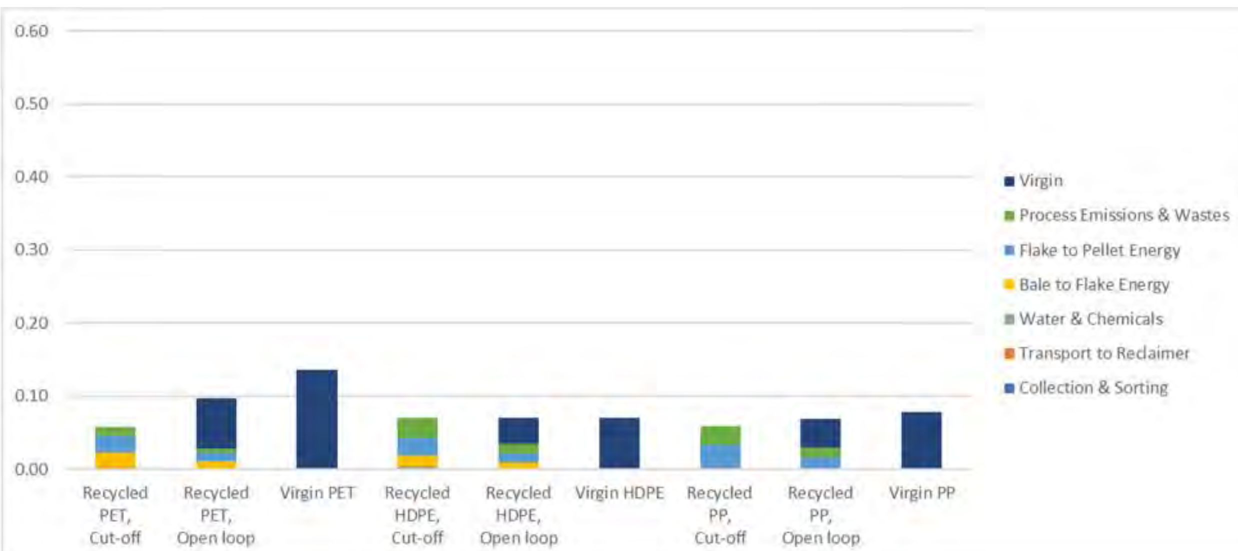


Figure 3-5. Solid Waste Results for Recycled and Virgin Resins, Excluding Contaminants in Incoming Material (kg waste/kg resin)

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.

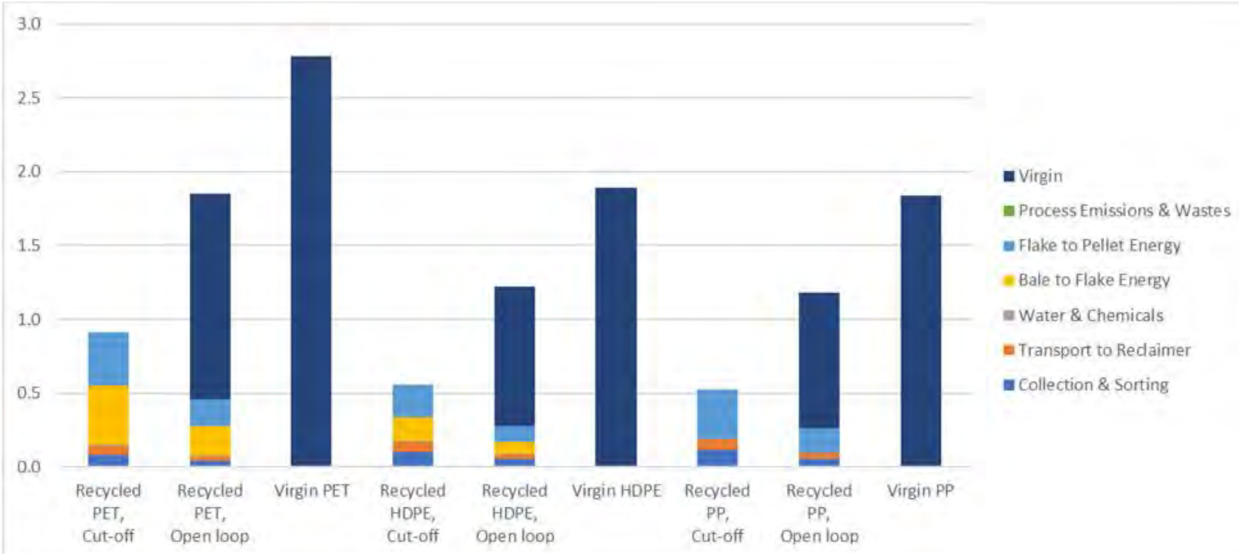


Figure 3-6. Global Warming Potential Results for Recycled and Virgin Resins (kg CO_2 eq/kg resin)

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.

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.

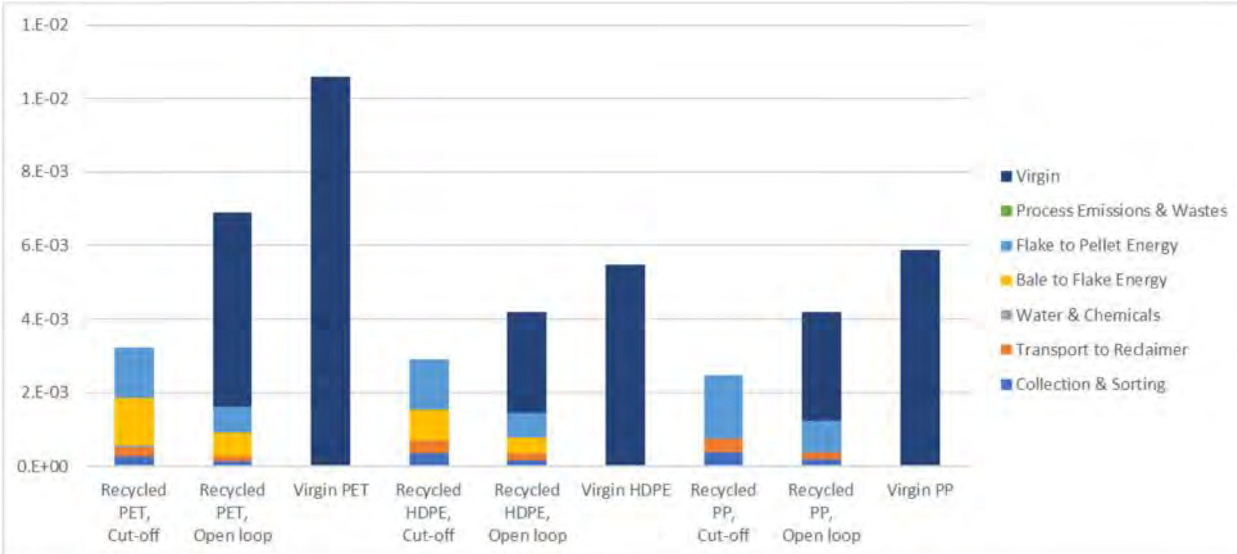


Figure 3-7. Acidification Potential Results for Recycled and Virgin Resins (kg SO_2 eq/kg resin)

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.

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.

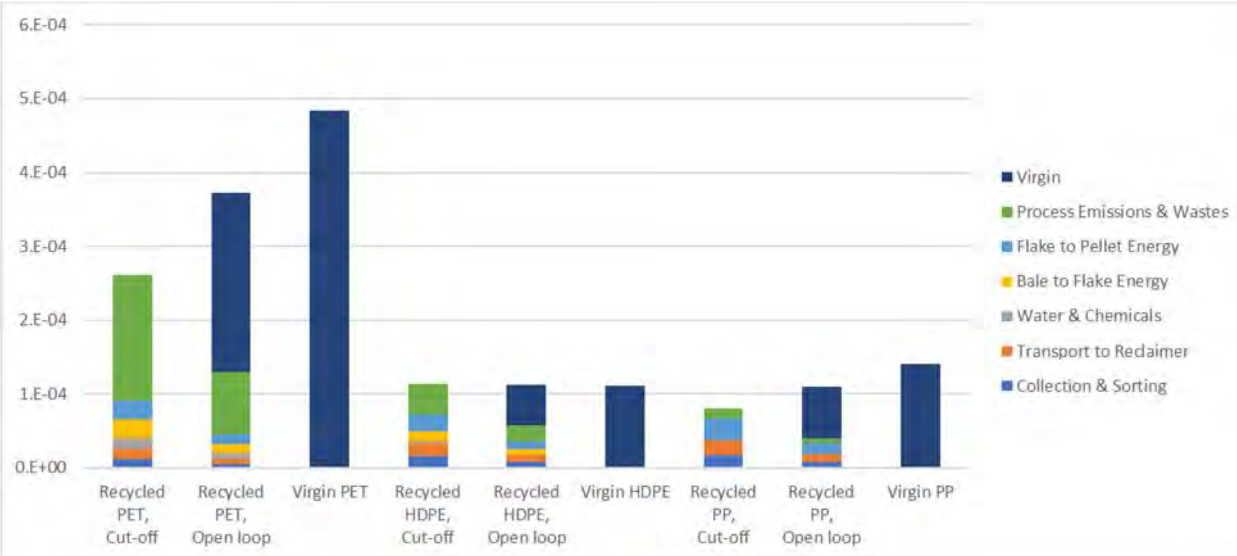


Figure 3-8. Eutrophication Potential Results for Recycled and Virgin Resins (kg N eq/kg resin)

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.

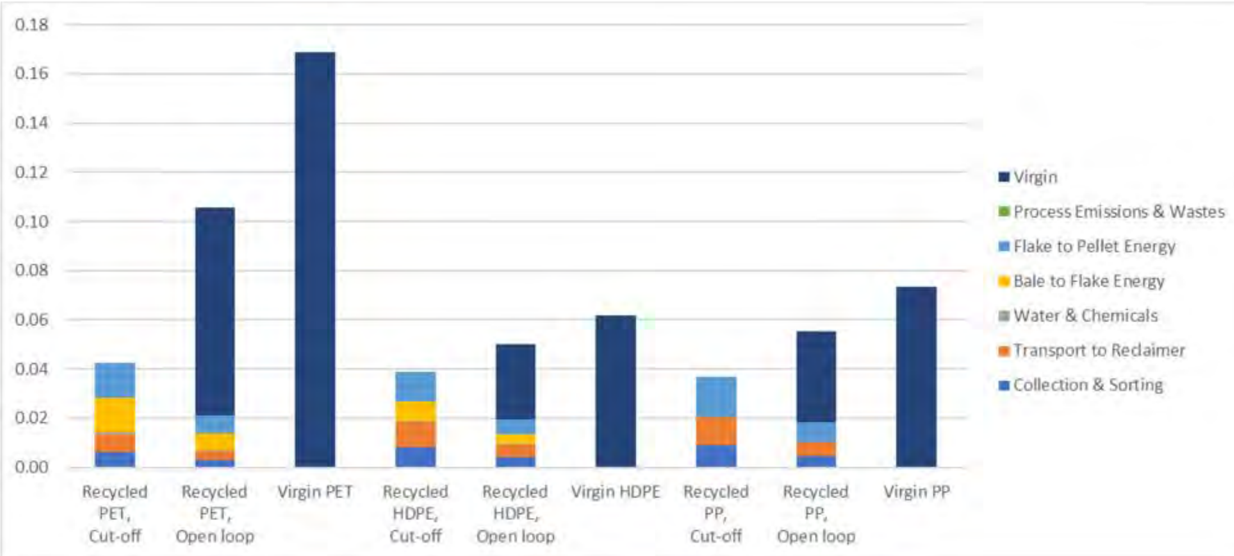


Figure 3-9. Smog Potential Results for Recycled and Virgin Resins (kg O_3 eq/kg resin)

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

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.

[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**

*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%

*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.

BOUSTEAD CONSULTING & ASSOCIATES

"FINAL REPORT"

Life Cycle Assessment for Three Types of Grocery Bags - Recyclable Plastic; Compostable, Biodegradable Plastic; and Recycled, Recyclable Paper

Prepared for the Progressive Bag Alliance

Chet Chaffee and Bernard R. Yaros
Boustead Consulting & Associates Ltd.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

In the pursuit to eliminate all that is not green, plastic seems to be a natural target. Its widespread use in products and packaging, some say, has contributed to environmental conditions ranging from increased pollution to overloaded landfills to the country's dependence on oil. In response, some cities have adopted legislation that bans plastic grocery bags made from polyethylene in favor of bags made from materials such as cloth, compostable plastics, or paper.

But will switching from grocery bags made from polyethylene to bags made from some other material guarantee the elimination of unfavorable environmental conditions? We know that every product—through its production, use, and disposal—has an environmental impact. This is due to the use of raw materials and energy during the production process and the emission of air pollutants, water effluents, and solid wastes.

More specifically, are grocery bags made other materials such as paper or compostable plastics really better for the environment than traditional plastic grocery bags? Currently, there is no conclusive evidence supporting the argument that banning single use plastic bags in favor of paper bags will reduce litter, decrease the country's dependence on oil, or lower the quantities of solid waste going to landfills. In addition, there is limited information on the environmental attributes of compostable plastics and how they fare against traditional plastic grocery bags or paper bags.

To help inform the debate about the environmental impacts of grocery bags, the Progressive Bag Alliance contracted with Boustead Consulting & Associates (BCAL) to conduct a life cycle assessment (LCA) on three types of grocery bags: a traditional grocery bag made from polyethylene, a grocery bag made from compostable plastics (a blend of 65% EcoFlex, 10% polylactic acid or PLA, and 25% calcium carbonate), and a paper grocery bag made using at least 30% recycled fibers. The life cycle assessment factored in every step of the manufacturing, distribution, and disposal stages of these grocery bags. It was recognized that a single traditional plastic grocery bag may not have the same carrying capacity as a paper bag, so to examine the effect of carrying capacity, calculations were performed both on a 1:1 basis as well as an adjusted basis (1:1.5) paper to plastic.

BCAL compiled life cycle data on the manufacture of polyethylene plastic bags and compostable plastic bags from the Progressive Bag Alliance. In addition, BCAL information on the compostable plastic resin EcoFlex from the resin manufacturer BASF. BCAL completed the data sets necessary for conducting life cycle assessments using information extracted from The Boustead Model and Database as well as the technical literature. BCAL used the Boustead Model for LCA to calculate the life cycle of each grocery bag, producing results on energy use, raw material use, water use, air emissions, water effluents, and solid wastes.

The results show that single use plastic bags made from polyethylene have many advantages over both compostable plastic bags made from EcoFlex and paper bags made with a minimum of 30% recycled fiber.

	Impact Summary of Various Bag Types (Carrying Capacity Equivalent to 1000 Paper Bags)		
	Paper (30% Recycled Fiber)	**Compostable Plastic**	**Polyethylene**
Total Enegy Usage (MJ)	2622	2070	763
Fossil Fuel Use (kg)	23.2	41.5	14.9
Municipal Solid Waste (kg)	33.9	19.2	7.0
Greenhouse Gas Emissions (CO2 Equiv. Tons)	0.08	0.18	0.04
Fresh Water Usage (Gal)	1004	1017	58

When compared to 30% recycled fiber paper bags, polyethylene grocery bags use less energy in terms of fuels for manufacturing, less oil, and less potable water. In addition, polyethylene plastic grocery bags emit fewer global warming gases, less acid rain emissions, and less solid wastes. The same trend exists when comparing the typical polyethylene grocery bag to grocery bags made with compostable plastic resins—traditional plastic grocery bags use less energy in terms of fuels for manufacturing, less oil, and less potable water, and emit fewer global warming gases, less acid rain emissions, and less solid wastes.

The findings of this study were peer reviewed by an independent third party with significant experience in life cycle assessments to ensure that the results are reliable and repeatable. The results support the conclusion that any decision to ban traditional polyethylene plastic grocery bags in favor of bags made from alternative materials (compostable plastic or recycled paper) will result in a significant increase in environmental impacts across a number of categories from global warming effects to the use of precious potable water resources. As a result, consumers and legislators should re-evaluate banning traditional plastic grocery bags, as the unintended consequences can be significant and long-lasting.

Introduction

In the national effort to go green, several states, counties, and cities are turning their attention to plastic grocery bags made from polyethylene because of the perception that plastic bags contribute to local and global litter problems that affect marine life, occupy the much needed landfill space with solid waste, and increase U.S. dependence on oil.

To address these environmental issues, and perhaps in seeking to follow the example of other countries such as Australia and Ireland, legislators in several cities across the United States have proposed or have already passed ordinances banning single use polyethylene plastic grocery bags in favor of bags made from alternative materials such as cloth, paper, or compostable plastic. Legislators state that they believe that these new laws and proposals will reduce litter, reduce the use of fossil fuels, and improve the overall environmental impacts associated with packaging used to transport groceries.

Before we examine whether plastic bags cause more environmental impacts than the alternative materials proposed, we should first consider the most commonly proposed alternatives, which tend to include: cloth bags, compostable plastic bags, and paper bags.

Reusable cloth bags may be the preferred alternative, but in reality, there is no evidence that most, or even a majority of, customers will reliably bring reusable bags each time they go shopping.

Compostable plastic bags, although available, are in short supply as the technology still is new, and therefore cannot currently meet market demand. So it appears that the proposed laws banning plastic grocery bags may simply cause a shift from plastic bags to the only alternative that can immediately supply the demand—paper bags.

Therefore, is legislation that mandates one packaging material over another environmentally responsible given that all materials, products, and packaging have environmental impacts? The issue is whether the chosen alternatives will reduce one or several of the identified environmental impacts, and whether there are any trade-offs resulting in other, potentially worse, environmental impacts.

To help inform the debate on the environmental impacts of grocery bags, and identify the types and magnitudes of environmental impacts associated with each type of bag, the Progressive Bag Alliance contracted Boustead Consulting & Associates (BCAL) to conduct a life cycle assessment (LCA) on single use plastic bags as well as the two most commonly proposed alternatives: the recyclable paper bag made in part from recycled fiber and the compostable plastic bag.

Life cycle assessment is the method being used in this study because it provides a systems approach to examining environmental factors. By using a systems approach to analyzing environmental impacts, one can examine all aspects of the system used to produce, use, and dispose of a product. This is known as examining a product from cradle (the extraction of raw materials necessary for producing a product) to grave (final disposal of the product). LCA has been practiced since the early 1970s, and standardized through several organizations including SETAC (Society of Environmental Toxicology and Chemistry) and ISO (International Standards Organization). LCA studies examine the inputs (resources and energy) and outputs (air emissions, water effluents, and solid wastes) of each system and thus identifies and quantifies the effects of each system, providing insights into potential environmental impacts at local, regional, and global levels.

To compile all the information and make the calculations, BCAL uses the Boustead Model and Database. The Boustead Model and Database is an LCA software model with a database built over the past 25 years, containing a wide variety of data relevant to the proposed study. Dr. Boustead has pioneered the use of life-cycle methods and has conducted hundreds of studies, including those for the plastics industry; which have been reviewed by US and European industry as well as life-cycle practitioners.

Study Goal

According to ISO 14040, the first steps in a life cycle project are defining the goal and scope of the project to ensure that the final results meet the specific needs of the user. The purpose of this study is to inform the debate on the environmental impacts of grocery bags, and identify the types and magnitudes of environmental impacts associated with each type of bag. In addition, the study results aim to inform the reader about the potential for any environmental trade-offs in switching from grocery bags made from one material, plastic, to another, paper.

The life cycle assessment was conducted on three types of grocery bags: a traditional grocery bag made from polyethylene, a grocery bag made from compostable plastics (a blend of 65% EcoFlex, 10% polylactic acid or PLA, and 25% calcium carbonate), and a paper grocery bag made using at least 30% recycled fibers. It is important to note that the study looked at only one type of degradable plastic used in making grocery bags, which is the bag being studied by members of the Progressive Bag Alliance. Since this is only one of a number of potential blends of plastic that are marketed as degradable or compostable, the results of this study cannot be used to imply that all compostable bags have the same environmental profile.

Scope

The scope of the study is a cradle to grave life cycle assessment which begins with the extraction of all raw materials used in each of the bags through to the ultimate disposal of the bags after consumer use, including all the transport associated with the delivery of raw materials and the shipping and disposal of final product.

The function of the product system under study is the consumer use and disposal of a grocery bag. The functional unit is the capacity of the grocery bag to carry consumer purchases. A 1/6 BBL (Barrel) size bag was selected for all three bags in this study because that is the commonly used bag in grocery stores. Although the bags are of equal size, previous studies (Franklin, 1990) pointed out that the use of plastic bags in grocery stores was not equal to the use of paper bags. According to Franklin (1990), bagging behavior showed that plastic to paper use ranged from 1:1 all the way to 3:1, depending on the situation. In contrast, data collected by the Progressive Bag Alliance shows that plastic and paper bags are somewhat equal in use once the baggers have been properly trained. In this study BCAL used both 1:1 and 1.5:1 plastic to paper ratios, allowing for the possibility that it still takes more plastic bags to carry the same amount of groceries as a paper bag. The 1.5:1 ratio equates to 1500 plastic bags for every 1000 paper bags.

BCAL prepared LCA's for the three types of grocery bags. The data requirements for BCAL and for the Progressive Bag Alliance are outlined below.

1. *Recyclable Paper Bag LCA………The following operations are to be included in the analysis:* To start, BCAL provided data on the extraction of fuels and feedstocks from the earth, including tree growing, harvesting, and transport of all materials. BCAL added process operations in an integrated unbleached kraft pulp & paper mill including recycling facility for old corrugated containers; paper converting into bags; closed-loop recycling of converting bag waste; packaging and transport to distribution and grocery stores; consumer use; and final disposal. Data for most of the above operations in one form or another are in the Boustead Model and Database. Weyerhaeuser reported that its unbleached kraft grocery bag contains about 30% post consumer recycled content and the use of water-based inks[1]. Therefore, in this study BCAL used 30% recycled material. This is also somewhat reflective of current legislation where minimum recycled content in paper bags is required (see Oakland City Council Ordinance requiring 40% recycled material). In the operations leading to final disposal BCAL estimated data for curbside collection and generation and recovery of materials in MSW from government agencies and EPA data, which for 2005 showed paper bag recycling at 21%, paper bag MSW for combustion with energy recovery at 13.6%, resulting in 65.4% to landfill[2]. The following final disposal options will also be considered: composting and two landfill scenarios.

2. *Recyclable Plastic Bag LCA………The following operations are to be included in the analysis:* The extraction of fuels and feedstocks from the earth; transport of materials; all process and materials operations in the production of high and low density polyethylene resin[3]; converting PE resin into bags; packaging and transport of bags to distribution centers and grocery stores; consumer use; and final disposal. In the operations leading to final disposal, BCAL estimated data for curbside collection and generation and recovery of materials in MSW from government agencies and EPA data, which for 2005 showed plastic bag recycling at 5.2 %, plastic bag MSW for combustion with energy recovery at 13.6%, resulting in 81.2% to landfill[2]. The following final disposal options will also consider two landfill scenarios.

   Data for the converting operation was collected specifically from a member of the Progressive Bag Alliance that makes only plastic grocery bags. The data obtained, represents the entire annual production for 2006. All waste is reprocessed on site, so that is how the calculations were conducted. All inks are water-based, and the formulas provided. The production and supply of all PE resin is based on materials produced and transported from a Houston based supplier. The corrugated boxes were included as made from recycled material to reflect the fact that the supplier to the PBA member reported using between 30% and 40% post consumer recycled fiber[1].

3. *Degradable Plastic Bag (EcoFlex and PLA mix) LCA………The following operations are to be included in the analysis:* The extraction of fuels and feedstocks from the earth; production and transport of materials for all process and materials operations in the production of polylactide resin; EcoFlex from BASF (data provided by BASF)[4]; and calcium carbonate, converting the EcoFlex/PLA resin mixture into bags; packaging and transport of bags to distribution centers and grocery stores; consumer use; and final disposal. Again, most of the above operations are contained in the Boustead Model and Database. The production data for PLA was obtained from NatureWorks[5] and the data for EcoFlex was obtained from BASF[4]. Both NatureWorks and BASF use the Boustead Model for their LCA calculations, so the data BCAL requested and received was compatible with other data used in the study. In addition, BCAL sent its calculated results to BASF for confirmation that the data and the calculations on bags made from the EcoFlex compostable resin was accurate. BASF engineers confirmed that BCAL's use of the data and the calculated results were appropriate. In the operations leading to final disposal, BCAL estimated data for curbside collection and generation and recovery of materials in MSW from government agencies and EPA data[3], which for 2005 showed plastic bag recycling at 5.2 %, plastic bag MSW for combustion with energy recovery at 13.6%, resulting in 81.2% to landfill[2]. The following final disposal options will be also be considered: composting and two landfill scenarios.

   Data for the converting operation of the EcoFlex/PLA resin mixture was collected at the same PBA member facility during a two-week period at the end of May 2007. The production and supply of the PLA polymer is from Blair, NE. The production and supply of Ecoflex polymer is from a BASF plant in Germany. The trial operations at the PBA member's facility indicate that the overall energy required to produce a kilogram of EcoFlex/PLA bags may be lower than the overall energy required to produce a kilogram of PE bags, based on preliminary in-line electrical measurements conducted by plant engineers. However, these results still are preliminary, and need to be confirmed when full scale operations are implemented. As a result, this study will assume that the overall energy required to produce a kilogram of EcoFlex/PLA bags is the same as the overall energy required to produce a kilogram of PE bags. The plastic bag recycling at 5.2 %, will be assumed to go to composting. The inherent energy of the degradable bags has been estimated from NatureWorks and BASF sources.

The following are some detailed specifications for the LCA study:

	Recyclable Plastic	Degradable Plastic	Recyclable Paper
Size/type	1/6 BBL	1/6 BBL	1/6 BBL
Length (inches)	21.625	22.375	17
Width (inches)	12	11.5	12
Gusset (inches)	7.25	7.25	6.75
Gauge (Mil)	0.51	0.75	20 lb /1000 sq ft
Film Color	White	White	Kraft
Material	HDPE (film grade blend)	Degradable Film Compound (EcoFlex/PLA mix)	Unbleached Kraft Paper
Jog Test (strokes)	45	20	n/a
Tensile Strength (lb)	50	35	n/a
Weight per 1000 bags in lbs	13.15 (5.78 kg)	34.71 (15.78 kg)	114 (51.82 kg)

Human energy and capital equipment will not be included in the LCA; detailed arguments for this decision are presented in the proposal appendix.

Methodological Approach

BCAL followed the sound scientific practices as described in ISO 14040, 14041, and 14042 to produce the project results. BCAL is well versed in the requirements of the ISO standards as Dr. Ian Boustead has and continues to be one of the leading experts participating in the formation of the ISO standards. The procedures outlined below are consistent with the ISO standards and reflect BCAL's approach to this project.

Calculations of LCAs

The Boustead database contains over 6000 unit operations on the processes required to extract raw materials from the earth, process those materials into useable form, and manufacture products. These operations provide data on energy requirements, emissions and wastes.

The "Boustead Model" software was used to calculate the consumption of energy, fuels, and raw materials, and generation of solid, liquid, and gaseous wastes starting from the extraction of primary raw materials. The model consists of a calculating engine that was developed 25 years ago and has been updated regularly based on client needs and technical innovations. One important consequence of the modeling is that a mass balance for the entries system is calculated. Therefore, the resource use and the solid waste production are automatically calculated.

Fuel producing industry data are available for all of the OECD countries and some non-OECD countries. The United States and Canada are further analyzed by region; the US is divided into 9 regions and Canada is sub-divided in 5 regions, corresponding to the Electric Reliability Council. For both the US and Canada, there also is a national average. Since the whole of the Model database can be switched from one country to another, any operation with data from outside the US can be adjusted for energy from non-US energy inputs to “USA adjusted” energy inputs. Assuming that the technology is the same, or very similar, this allows BCAL to fill any data gaps with data from similar operations in non-US locations.

Another important aspect of calculating LCAs is the use of allocation procedures when differentiating the use of energy and raw materials associated with individual products within a single system. In many cases, allocation methods that defy or at the very least, ignore sound scientific practice (such as economics) have been used when they benefit clients. These types of errors or biases are important to avoid as they are easily discovered by peer reviewers or technical experts seeking to use the results in subsequent studies (such as building applications), which unfortunately can cause the rest of the work to be discounted due to unreliability. BCAL has considerable experience in this arena having published several technical papers on the appropriate allocation principles in the plastics industry. Utilizing sound scientific principles and objective measures to the greatest extent possible, BCAL has been able to avoid most problems associated with allocation decisions and produce accurate and reliable LCA data for a wide variety of plastics. Proof of this is the widespread use of PlasticsEurope data (produced by Boustead Consulting) in almost every life cycle database available worldwide as well as in life cycle studies in numerous product and building applications.

Calculated data are readily aggregated and used to produce the final LCA data set which includes the impact assessment step of LCA. These resulting data sets address specific environmental problems.

Using LCA data.…BCAL scientific viewpoint

Life cycle assessment modeling allows an examination of specific problems as well as comparisons between systems to determine if there are any serious trade-offs between systems. In every system there are multiple environmental parameters to be addressed scaling from global to local issues. No single solution is likely to address all of the issues simultaneously. More importantly, whenever choices are being made to alter a system or to utilize an alternative system, there are potential trade-offs. Understanding those trade-offs is important when trying to identify the best possible environmental solution. Hopefully, decisions to implement a change to an existing system will consider the potential trade-offs and compromises. While LCA can identify the environmental factors and trade-offs, choosing the solution that is optimal is often subjective and political. Science can only help by providing good quality data from which decisions can be made. The strength of the proposed LCA assessment system is that these unwanted side effects can be identified and quantified.

A life cycle assessment can:

1. Quantify those parameters likely to be responsible for environmental effects (the inventory component of life cycle analysis).

2. Identify which parameters are likely to contribute to a specific environmental problem (characterization or interpretation phase of impact assessment). An example would be identifying that carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are greenhouse gases.
3. Aggregate the parameters relating to a specific problem (the valuation or interpretation phase of impact assessment). An example would be producing carbon dioxide equivalents for the components of greenhouse gases.

LCA derived data provide a compilation of information from which the user can address specific problems, while also examining potential trade-offs. For example, if interested in addressing specific conservation issues such as the conservation of fossil fuels, the user would examine the mass and energy data for only coal, oil, and natural gas; and ignore the other information. If the user would like to examine the potential impacts the grocery bag system has on global warming, acid rain, and municipal solid waste one can address these issues both individually and cooperatively by examining the specific parameters which are likely to contribute to each. In so doing, the user can strive to achieve the optimum reduction in each parameter because of a better understanding of how these parameters change in association with the grocery bag system as a whole and each other individually.

Data Sources and Data Quality

As noted above, data sources included published reports on similar materials, technical publications dealing with manufacturing processes, and data incorporated into the Boustead Model and Database, most of which has been generated through 30 years of industrial studies on a wide range of products and processes.

ISO standards 14040, 14041, and 14042 each discuss aspects of data quality as it pertains to life cycle assessments. In general, data quality can be evaluated using expert judgment, statistics, or sensitivity analysis. In LCA studies, much of the data do not lend itself to statistical analyses as the data are not collected randomly or as groups of data for each input variable. Instead, most LCA data are collected as single point estimates (i.e., fuel input, electricity input, product output, waste output, etc). Single point estimates are therefore only able to be evaluated through either expert judgment or sensitivity analysis. Since the reliability of data inevitably depends upon the quality of the information supplied by individual operators, BCAL used its expert judgment to carry out a number of elementary checks on quality. BCAL checked mass and energy balances to ensure that the data did not violate any of the basic physical laws. In addition, BCAL checked data from each source against data from other sources in the Boustead Model and Database to determine if any data fell outside the normal range for similar products or processes.

Data reporting

To enhance the comparability and understanding of the results of this study, the detailed LCA results are presented in the same presentation format that was used for the series of eco-profile reports published by the Association of Plastics Manufacturers in Europe

(APME). A set of eight tables, each describing some aspect of the behavior of the system, shows the results of the study. Five tables in the data set are useful in conservation arguments and three tables are indications of the potential pollution effects of the system.

The performance of the grocery bag systems is described by quantifying the inputs and outputs to the system. The calculation of input energy and raw materials quantifies the demand for primary inputs to the system and these parameters are important in conservation arguments because they are a measure of the resources that must be extracted from the earth in order to support the system.

Calculation of the outputs is an indication of the potential pollution effects of the system. Note that the analysis is concerned with quantifying the emissions; it does not make any judgments about deleterious or beneficial properties.

The inputs and outputs depend on the definition of the system—they are interrelated. Therefore, any changes to the components of the system means that the inputs and outputs will likely change as well. One common misconception is that it is possible to change a single input or output while leaving all other parameters unchanged. In fact, the reverse is true; because a new system has been defined by changing one input or output, all of the inputs and outputs are expected to change. If they happen to remain the same, it is a coincidence. This again illustrates the fact that common perceptions about environmental gains from simple changes may be misleading at best, and detrimental to the environment at worst.

Increasingly there is a demand to have the results of eco-profile analyses broken down into a number of categories, identifying the type of operation that gives rise to them. The five categories that have been identified are:

1. Fuel production
2. Fuel use
3. Transport
4. Biomass
5. Process

Fuel production operations are defined as those processing operations which result in the delivery of fuel, or energy; to a final consumer whether domestic or industrial. For such operations all inputs, with the sole exception of transport, are included as part of the fuel production function.

Fuel use is defined as the use of energy delivered by the fuel producing industries. Thus fuel used to generate steam at a production plant and electricity used in electrolysis would be treated as fuel use operations. Only the fuel used in transport is kept separate.

Transport operations are easily identified and so the direct energy consumption of transport and its associated emissions are always separated.

Biomass refers to the inputs and outputs associated with the use of biological materials such as wood or wood fiber.

LCA RESULTS TABLES

RECYCLABLE PAPER BAG SYSTEM

The results of the LCA for the recyclable paper bag system are presented below, each describing some aspect of the behavior of the systems examined. In all cases, the following tables refer to the gross or cumulative totals when all operations are traced back to the extraction of raw materials from the earth and are based on the consumer use and collection of 1000 bags. The subsequent disposal operations of recycling, composting, incineration with energy recovery and landfill are not included in these results tables and will be discussed separately.

Table 1. Gross energy (in MJ), required for the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Electricity	461	185	3	0	649
Oil	17	143	30	1	191
Other	15	777	1	990	1783
Total	493	1105	34	991	2622

Table 2. Gross primary fossil fuels and feedstocks, expressed as energy (in MJ), required for the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Feedstock	Total
Coal	229	94	1	0	324
Oil	23	150	33	1	207
Gas	113	278	0	0	391
Hydro	15	6	0	-	21
Nuclear	90	36	0	-	127
Lignite	0	0	0	-	0
Wood	0	533	0	988	1521
Sulfur	0	0	0	2	2
Hydrogen	0	0	0	0	0
Biomass (solid)	18	7	0	0	24
Recovered energy	0	-1	0	-	-1
Geothermal	0	0	0	-	0
Unspecified	0	0	0	-	0
Solar	0	0	0	-	0
Biomass (liqd/gas)	1	0	0	-	1
Industrial waste	1	0	0	-	1
Municipal Waste	3	1	0	-	4
Wind	0	0	0	-	0
Totals	493	1105	34	991	2622

Table 3. Gross primary fossil fuels and feedstocks, expressed as mass (in milligrams), the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Crude oil……………..	4,591,000
Gas/condensate………	7,432,000
Coal………………….	11,210,000
Metallurgical coal…...	25,900
Lignite …………….	79
Peat ………………….	444
Wood (50% water)…..	274,000,000
Biomass (incl. water)…	2,880,000

Table 4. Gross water resources (in milligrams) required for the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Source	Use in process	Use in cooling	Totals
Public supply	3,895,000,000	-	3,895,000,000
River/canal	5,260	1,920	7,190
Sea	8,490	1,092,000	1,100,000
Unspecified	14,600,000	2,910,000	17,500,000
Well	200	50	250
Totals	3,909,000,000	4,000,000	3,913,000,000

Note: total cooling water reported in recirculating systems = 404.

Table 5. Gross other raw materials (in milligrams required for the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Raw material	Input in mg
Air	4,080,000
Animal matter	0
Barites	211
Bauxite	469
Bentonite	51
Biomass (including water)	0
Calcium sulphate (CaSO4)	0
Chalk (CaCO3)	0
Clay	46,300
Cr	31
Cu	0
Dolomite	792
Fe	64,800
Feldspar	0
Ferromanganese	59
Fluorspar	9
Granite	0
Gravel	239
Hg	0
Limestone (CaCO3)	385,000
Mg	0
N2	6,050
Ni	0
O2	1,180
Olivine	608
Pb	395
Phosphate as P205	147,000
Potassium chloride (KCl)	7
Quartz (SiO2)	0
Rutile	0
S (bonded)	1
S (elemental)	233,000
Sand (SiO2)	101,600
Shale	1
Sodium chloride (NaCl)	712,000
Sodium nitrate (NaNO3)	0
Talc	0
Unspecified	0
Zn	14

Table 6. Gross air emissions (in milligrams) resulting from the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Air emissions/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Fugitive	Total
Dust	32,900	4,440	1,930	89,000	-	-	128,000
CO	59,500	16,300	23,000	21,900	-	-	121,000
CO2	43,100,000	22,600,000	2,330,000	1,066,000	-63,600,000	-	5,507,000
SOX	168,000	166,000	6,030	239,000	-	-	579,000
NOX	151,000	86,400	26,500	600	-	-	264,000
N2O	<1	<1	-	-	-		<1
Hydrocarbons	49,000	16,000	7,300	60	-		72,300
Methane	266,000	16,200	10	3,500	-		286,000
H2S	<1	-	<1	2,750	-	-	2,750
Aromatic HC	6	-	98	1	-	-	105
HCl	6,440	42	4	622	-		7,110
Cl2	<1	-	<1	<1	-		<1
HF	242	2	<1	<1	-		244
Lead	<1	<1	<1	<1	-		<1
Metals	25	105	-	<1	-		131
F2	<1	-	<1	<1	-		<1
Mercaptans	<1	<1	<1	802	-	-	802
H2	124	<1	<1	91	-	-	215
Organo-chlorine	<1	-	<1	<1	-		<1
Other organics	<1	<1	<1	<1	-		1
Aldehydes (CHO)	-	-	-	13	-		13
Hydrogen (H2)	152	-	-	3,130	-		3,280
NMVOC	2	-	<1	<1	-		2

Table 6B. Carbon dioxide equivalents corresponding to the gross air emissions (in milligrams) resulting from the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Type/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equiv	59,850,000	23,690,000	2,400,000	1,330,000	-63,560,000	23,710,000
100 year equiv	49,460,000	23,060,000	2,400,000	1,190,000	-63,560,000	12,550,000
500 year equiv	45,200,000	22,800,000	2,400,000	1,130,000	-63,560,000	7,970,000

Table 7. Gross water emissions (in milligrams), resulting from the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags.. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Process	Total
COD	55	-	35	396,000	396,000
BOD	14	-	<1	75,000	75,000
Acid (H+)	11	-	<1	1	13
Al+compounds as Al	<1	-	<1	<1	<1
Ammonium compounds as NH4	19	-	2	<1	22
AOX	<1	-	<1	<1	<1
As+compounds as As	-	-	<1	<1	<1
BrO3--	<1	-	<1	<1	<1
Ca+compounds as Ca	<1	-	<1	19	20
Cd+compounds as Cd	-	-	<1	-	<1
Cl-	25	-	35	10,400	10,400
ClO3--	<1	-	<1	97	97
CN-	<1	-	<1	<1	<1
CO3--	-	-	3	30	34
Cr+compounds as Cr	<1	-	<1	<1	<1
Cu+compounds as Cu	<1	-	<1	<1	<1
Detergent/oil	<1	-	2	3	6
Dichloroethane (DCE)	<1	-	<1	<1	<1
Dioxin/furan as Teq	-	-	<1	-	<1
Dissolved chlorine	<1	-	<1	<1	<1
Dissolved organics (non-HC)	23	-	<1	<1	23
Dissolved solids not specified	1	-	9	3,700	3,710
F-	<1	-	<1	<1	<1
Fe+compounds as Fe	<1	-	2	<1	3
Hg+compounds as Hg	<1	-	<1	<1	<1
Hydrocarbons not specified	<1	<1	2	<1	3
K+compounds as K	<1	-	<1	<1	<1
Metals not specified elsewhere	3	-	<1	3,060	3,060
Mg+compounds as Mg	<1	-	<1	<1	<1
Mn+compounds as Mn	-	-	<1	<1	<1
Na+compounds as Na	10	-	22	7,510	7,540
Ni+compounds as Ni	<1	-	<1	<1	<1
NO3-	1	-	<1	76	78
Organo-chlorine not specified	<1	-	<1	6	6
Organo-tin as Sn	-	-	<1	-	<1
Other nitrogen as N	3	-	<1	7,950	7,950
Other organics not specified	<1	-	<1	<1	<1
P+compounds as P	<1	-	<1	879	880
Pb+compounds as PB	<1	-	<1	<1	<1
Phenols	<1	-	<1	<1	<1
S+sulphides as S	<1	-	<1	344	344
SO4--	<1	-	8	1536	1,544
Sr+compounds as Sr	-	-	<1	<1	<1
Suspended solids	2,850	-	3,870	219,800	226,500
TOC	<1	-	<1	<1	<1
Vinyl chloride monomer	<1	-	<1	<1	<1
Zn+compounds as Zn	<1	-	<1	<1	<1

Table 8. Generation of solid waste (in milligrams resulting from the recyclable PAPER bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Solid waste (mg)	Fuel prod'n	Fuel use	Transport	Process	Total
Construction waste	<1	-	<1	<1	<1
Inert chemical	<1	-	<1	275	276
Metals	<1	-	<1	1,350	1,350
Mineral waste	2,590	-	38,500	1889,000	230,000
Mixed industrial	-26,300	-	1,550	22,900	-1,860
Municipal solid waste	-383,000	-	-	-	-383,000
Paper	<1	-	<1	<1	<1
Plastic containers	<1	-	<1	-	<1
Plastics	<1	-	<1	389	390
Putrescibles	<1	-	11	<1	11
Regulated chemicals	67,500	-	3	85	67,600
Slags/ash	921,000	5,290	15,000	5,380	947,000
Tailings	81	-	1,290	4	1,380
Unregulated chemicals	51,200	-	51	820	52,040
Unspecified refuse	55,300	-	<1	282,000	337,000
Waste returned to mine	2,202,000	-	1,420	345	2,203,000
Waste to compost	-	-	-	1,290,000	1,290,000
Waste to incinerator	1	-	18	16	35
Waste to recycle	<1	-	<1	2,544,000	2,544,000
Wood waste	<1	-	<1	306,000	306,000
Wood pallets to recycle	<1	-	<1	-	<1

RECYCLABLE PLASTIC BAG SYSTEM

The results of the LCA for the recyclable plastic bag system are presented below, each describing some aspect of the behavior of the systems examined. In all cases, the following tables refer to the gross or cumulative totals when all operations are traced back to the extraction of raw materials from the earth and are based on the consumer use and collection of 1000 bags and 1500 bags. The subsequent disposal operations of recycling, composting, incineration with energy recovery and landfill are not included in these results tables and will be discussed separately.

Table 9A. Gross energy (in MJ), required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Electricity	103	42	3	0	148
Oil	2	35	7	156	199
Other	2	37	0	123	162
Total	106	114	11	279	509

Table 9B. Gross energy (in MJ), required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Electricity	154	63	5	0	222
Oil	3	53	11	233	299
Other	2	55	1	185	242
Total	159	171	16	418	763

Table 10A. Gross primary fossil fuels and feedstocks, expressed as energy (in MJ), required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Feedstock	Total
Coal	43	21	1	0	65
Oil	5	37	8	155	206
Gas	23	46	1	116	186
Hydro	4	2	0	-	6
Nuclear	26	11	1	-	38
Lignite	0	0	0	-	0
Wood	0	3	0	7	9
Sulfur	0	0	0	0	0
Hydrogen	0	0	0	-	0
Biomass (solid)	3	1	0	0	4
Recovered energy	0	-7	0	-	-7
Geothermal	0	0	0	-	0
Unspecified	0	0	0	-	0
Solar	0	0	0	-	0
Biomass (liqd/gas)	0	0	0	-	0
Industrial waste	0	0	0	0	0
Municipal Waste	1	0	0	-	1
Wind	0	0	0	-	0
Totals	106	114	11	279	509

Table 10B. Gross primary fossil fuels and feedstocks, expressed as energy (in MJ), required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags**.** Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Feedstock	Total
Coal	65	31	2	0	98
Oil	8	56	12	233	309
Gas	35	69	2	175	279
Hydro	6	3	0	-	9
39	16	1	1	-	57
Lignite	0	0	0	-	0
Wood	0	4	0	10	14
Sulfur	0	0	0	0	0
Hydrogen	0	0	0	-	0
Biomass (solid)	4	2	0	0	6
Recovered energy	0	-11	0	-	-11
Geothermal	0	0	0	-	0
Unspecified	0	0	0	-	0
Solar	0	0	0	-	0
Biomass (liqd/gas)	0	0	0	-	0
Industrial waste	0	0	0	0	0
Municipal Waste	1	0	0	-	1
Wind	0	0	0	-	0
Totals	159	171	16	418	763

Table 11A. Gross primary fossil fuels and feedstocks, expressed as mass (in milligrams), required the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Crude oil……………..	4,571,000
Gas/condensate………	3,065,000
Coal………………….	2,259,000
Metallurgical coal…...	6,060
Lignite …………….	670
Peat ………………….	7,920
Wood (50% water)…..	809,000
Biomass (incl. water)…	498,000

Table 11B. Gross primary fossil fuels and feedstocks, expressed as mass (in milligrams), required the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Crude oil……………..	6,857,000
Gas/condensate………	4,598,000
Coal………………….	3,388,000
Metallurgical coal…...	9,100
Lignite …………….	1,010
Peat ………………….	11,900
Wood (50% water)…..	1,212,000
Biomass (incl. water)…	746,000

Table 12A. Gross water resources (in milligrams) required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Source	Use in process	Use in cooling	Totals
Public supply	31,900,000	1,230,000	33,150,000
River/canal	4,970,000	2,520,000	7,480,000
Sea	819,000	58,600,000	59,400,000
Unspecified	5,120,000	105,400,000	110,600,000
Well	425,000	66,000	138,000
Total	43,250,000	167,800,000	211,100,000

Table 12B. Gross water resources (in milligrams) required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Source	Use in process	Use in cooling	Totals
Public supply	47,900,000	1,850,000	49,700,000
River/canal	7,460,000	3,780,000	11,200,000
Sea	1,230,000	87,900,000	89,100,000
Unspecified	7,680,000	158,000,000	166,000,000
Well	638,000	99,000	207,000
Total	64,900,000	252,000,000	317,000,000

Table 13A. Gross other raw materials (in milligrams required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Raw material	Input in mg
Air	1,436,000
Animal matter	<1
Barites	343
Bauxite	111
Bentonite	231
Calcium sulphate ($CaSO_4$)	22
Clay	235
Cr	7
Cu	<1
Dolomite	184
Fe	15,000
Feldspar	<1
Ferromanganese	14
Fluorspar	3
Granite	<1
Gravel	56
Hg	<1
Limestone ($CaCO_3$)	542,000
Mg	<1
N_2	823,000
Ni	<1
O_2	110,000
Olivine	141
Pb	87
Phosphate as P205	743
Potassium chloride (KCl)	252
Quartz (SiO_2)	0
Rutile	272,000
S (bonded)	13
S (elemental)	1,520
Sand (SiO_2)	935
Shale	63
Sodium chloride (NaCl)	51,200
Sodium nitrate ($NaNO_3$)	0
Talc	<1
Unspecified	<1
Zn	266

Table 13B. Gross other raw materials (in milligrams required for the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Raw material	Input in mg
Air	2,154,000
Animal matter	<1
Barites	515
Bauxite	166
Bentonite	347
Calcium sulphate (CaSO4)	33
Clay	353
Cr	10
Cu	<1
Dolomite	276
Fe	22,600
Feldspar	<1
Ferromanganese	21
Fluorspar	4
Granite	<1
Gravel	83
Hg	<1
Limestone (CaCO3)	812,000
Mg	<1
N2	1,235,000
Ni	<1
O2	165,000
Olivine	212
Pb	131
Phosphate as P205	1,120
Potassium chloride (KCl)	379
Quartz (SiO2)	0
Rutile	408,000
S (bonded)	20
S (elemental)	2,270
Sand (SiO2)	1,400
Shale	94
Sodium chloride (NaCl)	76,700
Sodium nitrate (NaNO3)	0
Talc	<1
Unspecified	<1
Zn	399

Table 14A. Gross air emissions (in milligrams) resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Air emissions/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Fugitive	Total
Dust (PM10)	6,340	540	430	7,000	-	-	14,300
CO	10,800	48,900	5,110	2,570	-	-	67,400
CO2	8,570,000	5,390,000	551,000	953,000	-427,000	-	15,030,000
SOX as SO2	35,700	9,130	2,000	3,640	-	-	50,500
H2S	<1	-	<1	14	-	-	14
Mercaptan	<1	<1	-	4	-		4
NOX as NO2	28,500	10,000	6,060	870	-	-	45,400
Aledhyde (-CHO)	<1	-	<1	<1	-	-	<1
Aromatic HC not spec	1	-	22	380	-	-	403
Cd+compounds as Cd	<1	-	<1	-	-		<1
CH4	40,900	1,660	3	20,700	-	-	63,300
Cl2	<1	-	<1	29	-	-	29
Cr+compounds as Cr	<1	-	<1	-	-	-	<1
CS2	<1	-	<1	<1	-		<1
Cu+compounds as Cu	<1	-	<1	-	-	-	<1
Dichlorethane (DCE)	<1	-	<1	<1	-	<1	<1
Ethylene C2H4	-	-	<1	-	-	-	<1
F2	<1	-	<1	<1	-	-	<1
H2	68	2	<1	754	-	-	824
H2SO4	<1	-	<1	<1	-	-	<1
HCl	1,220	95	<1	3	-	-	1,320
HCN	<1	-	<1	<1	-	-	<1
HF	46	1	<1	<1	-	-	47
Hg+compounds as Hg	<1	-	<1	<1	--	-	<1
Hydrocarbons not spec	7,430	920	1,670	13,100	-	-	23,100
Metals not specified	6	5	<1	3	-	-	14
Methylene chloride CH2	<1	-	<1	<1	-	-	<1
N2O	<1	<1	<1	-	-	-	<1
NH3	<1	-	<1	8	-	-	8
Ni compounds as Ni	<1	-	<1	-	-	-	<1
NMVOC	<1	-	<1	993	-	-	994
Organics	<1	<1	<1	367	-	-	367
Organo-chlorine not spec	<1	-	<1	<1	-	-	<1
Pb+compounds as Pb	<1	<1	<1	<1	-	-	<1
Polycyclic hydrocarbon	<1	-	<1	<1	-	-	<1
Sb+compounds as Sb	-	-	<1	-	-	-	<1
Vinyl chloride monomer	<1	-	<1	<1	-	<1	<1
Zn+compounds as Zn	<1	-	<1	<1	-	-	<1

Table 14B. Carbon dioxide equivalents corresponding to the gross air emissions (in milligrams) resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Type/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equiv	11,100,000	5,590,000	566,000	2,280,000	-427,000	19,200,000
100 year equiv	9,550,000	5,530,000	566,000	1,470,000	-427,000	16,700,000
500 year equiv	8,900,000	5,500,000	566,000	1,140,000	-427,000	15,700,000

Table 14C. Gross air emissions (in milligrams) resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Air emissions/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Fugitive	Total
Dust (PM10)	9,500	811	644	10,500	-	-	21,500
CO	16,100	73,400	7,670	3,850	-	-	101,000
CO2	12,900,000	8,082,000	826,000	1,429,000	-640,000	-	22,550,000
SOX as SO2	53,500	13,700	3,000	5,460	-	-	75,700
H2S	<1	-	<1	21	-	-	22
Mercaptan	<1	<1	-	6	-		6
NOX as NO2	42,700	15,100	9,090	1,310	-	-	68,100
Aledhyde (-CHO)	<1	-	<1	<1	-	-	<1
Aromatic HC not spec	2	-	33	570	-	-	604
Cd+compounds as Cd	<1	-	<1	-	-		<1
CH4	61,400	2,490	4	31,090	-	-	95,000
Cl2	<1	-	<1	43	-	-	43
Cr+compounds as Cr	<1	-	<1	-	-	-	<1
CS2	<1	-	<1	<1	-		<1
Cu+compounds as Cu	<1	-	<1	-	-	-	<1
Dichlorethane (DCE)	<1	-	<1	<1	-	<1	<1
Ethylene C2H4	-	-	<1	-	-	-	<1
F2	<1	-	<1	<1	-	-	<1
H2	102	2	<1	1,130	-	-	1,240
H2SO4	<1	-	<1	<1	-	-	<1
HCl	1,830	142	1	5	-	-	1,980
HCN	<1	-	<1	<1	-	-	<1
HF	69	2	<1	<1	-	-	71
Hg+compounds as Hg	<1	-	<1	<1	--	-	<1
Hydrocarbons not spec	11,100	1,380	2,510	19,700	-	-	34,700
Metals not specified	9	7	<1	5	-	-	21
Methylene chloride CH2	<1	-	<1	<1	-	-	<1
N2O	<1	<1	<1	-	-	-	<1
NH3	<1	-	<1	12	-	-	12
Ni compounds as Ni	<1	-	<1	-	-	-	<1
NMVOC	<1	-	<1	1,490	-	-	1,490
Organics	<1	<1	<1	551	-	-	551
Organo-chlorine not spec	<1	-	<1	<1	-	-	<1
Pb+compounds as Pb	<1	<1	<1	<1	-	-	<1
Polycyclic hydrocarbon	<1	-	<1	<1	-	-	<1
Sb+compounds as Sb	-	-	<1	-	-	-	<1
Vinyl chloride monomer	<1	-	<1	<1	-	<1	<1
Zn+compounds as Zn	<1	-	<1	<1	-	-	<1

Table 14D. Carbon dioxide equivalents corresponding to the gross air emissions (in milligrams) resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Type/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equiv	16,700,000	8,390,000	849,000	3,420,000	-641,000	28,800,000
100 year equiv	14,300,000	8,300,000	849,000	2,210,000	-641,000	25,100,000
500 year equiv	13,400,000	8,250,000	849,000	1,710,000	-641,000	23,600,000

Table 15A. Gross water emissions (in milligrams), resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Process	Total
COD	9	-	8	5390	5,410
BOD	2	-	<1	543	545
Acid (H+)	4	-	<1	9	13
Al+compounds as Al	<1	-	<1	4	4
Ammonium compounds as NH4	5	-	<1	11	17
AOX	<1	-	<1	<1	<1
As+compounds as As	-	-	<1	<1	<1
BrO3--	<1	-	<1	<1	<1
Ca+compounds as Ca	<1	-	<1	20	20
Cd+compounds as Cd	-	-	<1	-	<1
Cl-	3	-	8	3,060	3,070
ClO3--	<1	-	<1	15	15
CN-	<1	-	<1	<1	<1
CO3--	-	-	<1	181	182
Cr+compounds as Cr	<1	-	<1	<1	<1
Cu+compounds as Cu	<1	-	<1	1	1
Detergent/oil	<1	-	<1	39	40
Dichloroethane (DCE)	<1	-	<1	<1	<1
Dioxin/furan as Teq	-	-	<1	-	<1
Dissolved chlorine	<1	-	<1	<1	<1
Dissolved organics (non-HC)	3	-	<1	44	47
Dissolved solids not specified	2	-	2	947	952
F-	<1	-	<1	<1	<1
Fe+compounds as Fe	<1	-	<1	<1	<1
Hg+compounds as Hg	<1	-	<1	<1	<1
Hydrocarbons not specified	26	<1	<1	3	30
K+compounds as K	<1	-	<1	11	11
Metals not specified elsewhere	<1	-	<1	54	55
Mg+compounds as Mg	<1	-	<1	<1	<1
Mn+compounds as Mn	-	-	<1	<1	<1
Na+compounds as Na	2	-	5	3,136	3,143
Ni+compounds as Ni	<1	-	<1	<1	<1
NO3-	1	-	<1	13	13
Organo-chlorine not specified	<1	-	<1	<1	<1
Organo-tin as Sn	-	-	<1	-	<1
Other nitrogen as N	<1	-	<1	46	47
Other organics not specified	<1	-	<1	<1	<1
P+compounds as P	<1	-	<1	7	7
Pb+compounds as PB	<1	-	<1	<1	<1
Phenols	<1	-	<1	10	10
S+sulphides as S	<1	-	<1	2	2
SO4--	<1	-	2	4,097	4,098
Sr+compounds as Sr	-	-	<1	<1	<1
Suspended solids	573	-	861	78,300	79,800
TOC	<1	-	<1	60	60
Vinyl chloride monomer	<1	-	<1	<1	<1
Zn+compounds as Zn	<1	-	<1	<1	<1

Table 15B. Gross water emissions (in milligrams), resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Process	Total
COD	14	-	12	8,080	8,110
BOD	3	-	<1	814	817
Acid (H+)	6	-	<1	13	19
Al+compounds as Al	<1	-	<1	5	5
Ammonium compounds as NH4	7	-	<1	17	25
AOX	<1	-	<1	<1	<1
As+compounds as As	-	-	<1	<1	<1
BrO3--	<1	-	<1	<1	<1
Ca+compounds as Ca	<1	-	<1	30	30
Cd+compounds as Cd	-	-	<1	-	<1
Cl-	5	-	11	4,590	4,610
ClO3--	<1	-	<1	22	22
CN-	<1	-	<1	<1	<1
CO3--	-	-	1	272	273
Cr+compounds as Cr	<1	-	<1	<1	<1
Cu+compounds as Cu	<1	-	<1	2	2
Detergent/oil	<1	-	<1	59	60
Dichloroethane (DCE)	<1	-	<1	<1	<1
Dioxin/furan as Teq	-	-	<1	-	<1
Dissolved chlorine	<1	-	<1	1	1
Dissolved organics (non-HC)	4	-	<1	66	70
Dissolved solids not specified	3	-	3	1,420	1,430
F-	<1	-	<1	<1	<1
Fe+compounds as Fe	<1	-	<1	<1	<1
Hg+compounds as Hg	<1	-	<1	<1	<1
Hydrocarbons not specified	39	<1	<1	4	45
K+compounds as K	<1	-	<1	16	16
Metals not specified elsewhere	1	-	<1	81	83
Mg+compounds as Mg	<1	-	<1	<1	<1
Mn+compounds as Mn	-	-	<1	<1	<1
Na+compounds as Na	3	-	8	4,700	4,710
Ni+compounds as Ni	<1	-	<1	<1	<1
NO3-	<1	-	<1	19	19
Organo-chlorine not specified	<1	-	<1	<1	<1
Organo-tin as Sn	-	-	<1	-	<1
Other nitrogen as N	1	-	<1	69	70
Other organics not specified	<1	-	<1	<1	<1
P+compounds as P	<1	-	<1	10	10
Pb+compounds as PB	<1	-	<1	<1	<1
Phenols	<1	-	<1	15	15
S+sulphides as S	<1	-	<1	3	3
SO4--	<1	-	3	6,150	6,150
Sr+compounds as Sr	-	-	<1	<1	<1
Suspended solids	860	-	1,290	117,500	119,600
TOC	<1	-	<1	90	90
Vinyl chloride monomer	<1	-	<1	<1	<1
Zn+compounds as Zn	<1	-	<1	1	1

Table 16A. Generation of solid waste (in milligrams resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Solid waste (mg)	Fuel prod'n	Fuel use	Transport	Process	Total
Construction waste	<1	-	<1	<1	<1
Inert chemical	<1	-	<1	3,446	3,446
Metals	<1	-	<1	301	301
Mineral waste	974	-	8,564	324,200	333,700
Mixed industrial	-11,800	-	345	5,520	-5,950
Municipal solid waste	-79,800	-	-	22,500	-57,300
Paper	<1	-	<1	<1	<1
Plastic containers	<1	-	<1	-	<1
Plastics	<1	-	<1	53,600	53,600
Putrescibles	<1	-	2	7	10
Regulated chemicals	9,040	-	<1	4,720	13,800
Slags/ash	180,000	4,460	3,330	1,660	189,000
Tailings	16	-	287	1,048	1,350
Unregulated chemicals	6,810	-	11	7,190	14,000
Unspecified refuse	7,350	-	<1	62,900	70,200
Waste returned to mine	443,000	-	316	872	444,400
Waste to compost	-	-	-	9,290	9,290
Waste to incinerator	<1	-	4	4,370	4,380
Waste to recycle	<1	-	<1	33,200	33,200
Wood waste	<1	-	<1	2,330	2,330
Wood pallets to recycle	<1	-	<1	298,000	298,000

Table 16B. Generation of solid waste (in milligrams resulting from the recyclable PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Solid waste (mg)	Fuel prod'n	Fuel use	Transport	Process	Total
Construction waste	<1	-	<1	<1	<1
Inert chemical	<1	-	<1	5,170	5,170
Metals	<1	-	<1	452	452
Mineral waste	1,460	-	12,800	486,000	501,000
Mixed industrial	-17,700	-	517	8,280	-8,930
Municipal solid waste	1119,700	-	-	33,800	-85,900
Paper	<1	-	<1	<1	<1
Plastic containers	<1	-	<1	-	<1
Plastics	<1	-	<1	80,400	80,400
Putrescibles	<1	-	4	11	14
Regulated chemicals	13,600	-	<1	7,080	20,600
Slags/ash	270,000	6,680	4,990	2,480	284,000
Tailings	24	-	430	1,570	2,030
Unregulated chemicals	10,200	-	17	10,800	21,000
Unspecified refuse	11,030	-	<1	94,300	105,400
Waste returned to mine	665,000	-	475	1,310	667,000
Waste to compost	-	-	-	13,900	13,900
Waste to incinerator	<1	-	6	6,560	6,560
Waste to recycle	<1	-	<1	49,800	49,800
Wood waste	<1	-	<1	3,500	3,500
Wood pallets to recycle	<1	-	<1	447,000	447,000

THE COMPOSTABLE PLASTIC BAG SYSTEM

The results of the LCA for the compostable plastic bag system are presented below, each describing some aspect of the behavior of the systems examined. In all cases, the following tables refer to the gross or cumulative totals when all operations are traced back to the extraction of raw materials from the earth and are based on the consumer use and collection of 1000 bags and 1500 bags. The subsequent disposal operations of recycling, composting, incineration with energy recovery and landfill are not included in these results tables and will be discussed separately.

Table 17A. Gross energy (in MJ), required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Electricity	221	103	1	0	325
Oil	29	279	36	1	345
Other	15	277	1	417	710
Total	265	659	38	418	1380

Table 17B. Gross energy (in MJ), required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Fuel type	Fuel prod'n & delivery	Energy content of fuel	Transport energy	Feedstock energy	Total energy
Electricity	331	154	2	0	487
Oil	44	418	54	1	518
Other	22	416	2	625	1065
Total	398	988	57	627	2070

Table 18A. Gross primary fossil fuels and feedstocks, expressed as energy (in MJ), required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Feedstock	Total
Coal	113	48	1	0	161
Oil	34	281	37	1	353
Gas	44	301	1	360	705
Hydro	7	2	0	-	9
Nuclear	62	11	0	-	74
Lignite	0	0	0	-	0
Wood	0	7	0	18	26
Sulfur	0	0	0	0	0
Hydrogen	0	0	0	0	0
Biomass (solid)	6	2	0	39	47
Recovered energy	-2	-5	0	-	-8
Geothermal	0	0	0	-	0
Unspecified	0	0	0	-	0
Solar	0	0	0	-	0
Biomass (liqd/gas)	0	0	0	-	0
Industrial waste	1	0	0	-	1
Municipal Waste	1	0	0	-	1
Wind	0	11	0	-	11
Totals	265	659	38	418	1,380

Table 18B. Gross primary fossil fuels and feedstocks, expressed as energy (in MJ), required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Feedstock	Total
Coal	169	72	1	0	241
Oil	51	422	55	1	529
Gas	65	451	1	540	1,057
Hydro	11	3	0	-	14
Nuclear	94	17	0	-	111
Lignite	0	0	0	-	0
Wood	0	11	0	27	38
Sulfur	0	0	0	0	0
Hydrogen	0	0	0	0	0
Biomass (solid)	9	4	0	58	71
Recovered energy	-4	-8	0	-	-11
Geothermal	0	0	0	-	0
Unspecified	0	0	0	-	0
Solar	0	0	0	-	0
Biomass (liqd/gas)	0	0	0	-	0
Industrial waste	1	0	0	-	1
Municipal Waste	1	1	0	-	2
Wind	0	16	0	-	16
Totals	398	988	57	627	2,070

Table 19A. Gross primary fossil fuels and feedstocks, expressed as mass (in milligrams), required the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Crude oil……………..	7,840,000
Gas/condensate………	14,020,000
Coal………………….	5,760,000
Metallurgical coal…...	17,000
Lignite …………….	0
Peat ………………….	7
Wood (50% water)…..	2,210,000
Biomass (incl. water)…	986,000

Table 19B. Gross primary fossil fuels and feedstocks, expressed as mass (in milligrams), required the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Crude oil……………..	11,760,000
Gas/condensate………	21,030,000
Coal………………….	8,630,000
Metallurgical coal…...	25,000
Lignite …………….	0
Peat ………………….	10
Wood (50% water)…..	3,310,000
Biomass (incl. water)…	1,480,000

Table 20A. Gross water resources (in milligrams) required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Source	Use in process	Use in cooling	Totals
Public supply	2,540,000,000	19,200,000	2,560,000,000
River/canal	3,870	1,690,000	1,700,000
Sea	13,100	2,710,000	2,720,000
Unspecified	36,600,000	6,270,000	42,900,000
Well	564,000	49	564,000
Totals	2,580,000,000	29,900,000	2,607,000,000

Table 20B. Gross water resources (in milligrams) required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Source	Use in process	Use in cooling	Totals
Public supply	3,810,000,000	28,800,000	3,840,000,000
River/canal	5,810	2,540,000	2,550,000
Sea	19,650	4,065,000	4,080,000
Unspecified	54,900,000	9,410,000	64,350,000
Well	846,000	74	846,000
Totals	3,870,000,000	44,900,000	3,910,000,000

Table 21A. Gross other raw materials (in milligrams) required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Raw material	Input in mg
Air	1,460,000
Animal matter	0
Barites	1,700
Bauxite	4,000
Bentonite	99
Calcium sulphate (CaSO4)	<1
Clay	34,200
Cr	19
Cu	0
Dolomite	513
Fe	47,300
Feldspar	0
Ferromanganese	38
Fluorspar	3
Granite	0
Gravel	155
Hg	0
Limestone (CaCO3)	4,230,000
Mg	0
N2 for reaction	17,900
Ni	0
O2 for reaction	1,030
Olivine	394
Pb	260
Phosphate as P205	12,300
Potassium chloride (KCl)	23,000
Quartz (SiO2)	0
Rutile	0
S (bonded)	401,000
S (elemental)	23,700
Sand (SiO2)	22,400
Shale	2
Sodium chloride (NaCl)	261,000
Sodium nitrate (NaNO3)	0
Talc	0
Unspecified	0
Zn	9

Table 21B. Gross other raw materials (in milligrams) required for the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Raw material	Input in mg
Air	2,190,000
Animal matter	0
Barites	2,550
Bauxite	6,010
Bentonite	148
Calcium sulphate (CaSO4)	<1
Clay	51,300
Cr	28
Cu	0
Dolomite	769
Fe	71,000
Feldspar	0
Ferromanganese	57
Fluorspar	5
Granite	0
Gravel	232
Hg	0
Limestone (CaCO3)	6,350,000
Mg	0
N2 for reaction	26,800
Ni	0
O2 for reaction	1,550
Olivine	591
Pb	390
Phosphate as P205	18,400
Potassium chloride (KCl)	34,500
Quartz (SiO2)	0
Rutile	0
S (bonded)	602,000
S (elemental)	35,500
Sand (SiO2)	33,600
Shale	3
Sodium chloride (NaCl)	392,000
Sodium nitrate (NaNO3)	0
Talc	0
Unspecified	0
Zn	14

Table 22A. Gross air emissions (in milligrams) resulting from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Air emissions/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Fugitive	Total
Dust (PM10)	9,120	520	1,500	42,200	-	-	53,400
CO	16,000	4,900	16,900	4,100	-	-	41,900
CO2	13,860,000	2,620,000	2,580,000	41,800,000	-4,230,000	-	56,600,000
SOX as SO2	54,900	7,210	21,100	192,000	-	-	275,000
H2S	0	0	1	40	-	-	41
Mercaptan	0	0	0	11	-		11
NOX as NO2	50,000	8,260	24,500	221,500	-	-	304,000
Aledhyde (-CHO)	0	0	0	0	-	-	0
Aromatic HC not spec	2	-	67	4	-	-	74
Cd+compounds as Cd	0	-	0	-	-		0
CFC/HCFC/HFC not sp	0	-	0	0	-		0
CH4	59,600	1,060	98	224,000	-	-	284,000
Cl2	0	-	0	0	-	-	0
Cr+compounds as Cr	0	-	0	-	-	-	0
CS2	0	-	0	0	-		0
Cu+compounds as Cu	0	-	0	-	-	-	0
Dichlorethane (DCE)	0	-	0	0	-	0	0
Ethylene C2H4	-	-	0	-	-	-	0
F2	0	-	0	0	-	-	0
H2	38	0	0	226	-	-	264
H2SO4	0	-	0	0	-	-	0
HCl	2,140	6	3	871	-	-	3,020
HCN	0	-	0	0	-	-	0
HF	81	0	0	0	-	-	81
Hg+compounds as Hg	0	-	0	0	--	-	0
Hydrocarbons not spec	13,800	1,720	6,400	100	-	-	22,000
Metals not specified	8	4	0	0	0	-	12
Molybdenum	-	-	-	1	-	-	1
N2O	0	0	0	53,100	-	-	53,100
NH3	0	-	0	39	-	-	39
Ni compounds as Ni	0	-	0	-	-	-	0
NMVOC	0	72	410	46,400	-	-	46,900
Organics	0	0	0	119	-	-	119
Organo-chlorine not spec	0	-	0	16	-	-	16
Pb+compounds as Pb	0	0	0	0	-	-	0
Polycyclic hydrocarbon	0	-	0	0	-	-	0
Titanium	-	-	-	119	-	-	119
Vinyl chloride monomer	0	-	0	0	-	-	0
Zn+compounds as Zn	0	-	0	0	-	-	0

Table 22B. Carbon dioxide equivalents corresponding to the gross air emissions (in milligrams) from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Type/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equiv	17,630,000	2,700,000	2,640,000	70,200,000	-4,230,000	89,000,000
100 year equiv	15,300,000	2,660,000	2,640,000	62,640,000	-4,230,000	79,000,000
500 year equiv	14,300,000	2,640,000	2,400,000	51,600,000	-4,230,000	67,000,000

Table 22C. Gross air emissions (in milligrams) resulting from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Air emissions/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Fugitive	Total
Dust (PM10)	13,700	780	2,260	63,400	-	-	80,100
CO	24,000	7,360	25,300	6,150	-	-	62,900
CO2	20,800,000	3,930,000	3,880,000	62,700,000	-6,340,000	-	84,900,000
SOX as SO2	82,400	10,800	31,600	288,000	-	-	413,000
H2S	0	0	2	60	-	-	62
Mercaptan	0	0	0	17	-		17
NOX as NO2	74,900	12,400	36,700	332,000	-	-	456,000
Aledhyde (-CHO)	0	0	0	0	-	-	0
Aromatic HC not spec	3	-	101	7	-	-	111
Cd+compounds as Cd	0	-	0	-	-		0
CFC/HCFC/HFC not sp	0	-	0	0	-		0
CH4	89,500	1,590	147	335,000	-	-	426,000
Cl2	0	-	0	0	-	-	0
Cr+compounds as Cr	0	-	0	-	-	-	0
CS2	0	-	0	0	-		0
Cu+compounds as Cu	0	-	0	-	-	-	0
Dichlorethane (DCE)	0	-	0	0	-	-	0
Ethylene C2H4	-	-	0	-	-	-	0
F2	0	-	0	0	-	-	0
H2	57	0	0	339	-	-	397
H2SO4	0	-	0	0	-	-	0
HCl	3,220	8	5	1,310	-	-	4,540
HCN	0	-	0	0	-	-	0
HF	121	0	0	0	-	-	122
Hg+compounds as Hg	0	-	0	0	--	-	0
Hydrocarbons not spec	20,600	2,580	9,590	150	-	-	33,000
Metals not specified	13	5	0	0	0	-	18
Molybdenum	-	-	-	2	-	-	2
N2O	0	0	0	79,600	-	-	79,600
NH3	0	-	0	59	-	-	59
Ni compounds as Ni	0	-	0	-	-	-	0
NMVOC	1	108	615	69,600	-	-	70,300
Organics	0	0	0	178	-	-	178
Organo-chlorine not spec	0	-	0	24	-	-	24
Pb+compounds as Pb	0	0	0	0	-	-	0
Polycyclic hydrocarbon	0	-	0	0	-	-	0
Titanium	-	-	-	178	-	-	178
Vinyl chloride monomer	0	-	0	0	-	-	0
Zn+compounds as Zn	0	-	0	0	-	-	0

Table 22D. Carbon dioxide equivalents corresponding to the gross air emissions (in milligrams) from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Type/mg	Fuel prod'n	Fuel use	Transport	Process	Biomass	Total
20 year equiv	26,400,000	4,050,000	3,960,000	105,300,000	-6,350,000	134,000,000
100 year equiv	23,000,000	3,990,000	3,960,000	94,000,000	-6,350,000	119,000,000
500 year equiv	21,500,000	3,960,000	3,600,000	77,400,000	-6,350,000	101,000,000

Table 23A. Gross water emissions (in milligrams), resulting from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Process	Total
COD	15	2	57	59,700	59,800
BOD	4	-	4	3,190	3,200
Acid (H+)	2	-	0	0	4
Al+compounds as Al	0	-	0	2	2
Ammonium compounds as NH4	5	-	2	0	7
AOX	0	-	0	10	10
As+compounds as As	-	-	0	0	0
BrO3--	0	-	0	0	0
Ca+compounds as Ca	0	-	0	201	201
Cd+compounds as Cd	-	-	0	-	0
Cl-	7	-	670	27,500	28,100
ClO3--	0	-	0	2	2
CN-	0	-	0	0	0
CO3--	-	-	2	5	7
Cr+compounds as Cr	0	-	0	0	0
Cu+compounds as Cu	0	-	0	0	0
Detergent/oil	0	-	2	3	5
Dichloroethane (DCE)	0	-	0	0	0
Dioxin/furan as Teq	-	-	0	-	0
Dissolved chlorine	0	-	0	0	0
Dissolved organics (non-HC)	6	-	0	0	6
Dissolved solids not specified	2	-	6	59	67
F-	0	-	6	0	6
Fe+compounds as Fe	0	-	1	20	22
Hg+compounds as Hg	0	-	0	0	0
Hydrocarbons not specified	0	0	1	334	337
K+compounds as K	0	-	0	2	2
Metals not specified elsewhere	0	-	0	52	52
Mg+compounds as Mg	0	-	0	2	2
Mn+compounds as Mn	-	-	0	0	0
Na+compounds as Na	3	-	15	1,270	1,290
Ni+compounds as Ni	0	-	0	0	0
NO3-	0	-	0	1,910	1,910
Organo-chlorine not specified	0	-	0	0	0
Organo-tin as Sn	-	-	0	-	0
Other nitrogen as N	0	-	0	4,300	4,300
Other organics not specified	0	-	0	0	0
P+compounds as P	0	-	0	41	41
Pb+compounds as PB	0	-	0	0	0
Phenols	0	-	0	0	0
S+sulphides as S	0	-	0	5	5
SO4--	0	-	5	6,287	6,290
Sr+compounds as Sr	-	-	0	0	0
Suspended solids	945	-	2,660	396,000	399,000
TOC	0	-	15	2,460	2,480
Vinyl chloride monomer	0	-	0	0	0
Zn+compounds as Zn	0	-	0	0	0

Table 23B. Gross water emissions (in milligrams), resulting from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

	Fuel prod'n	Fuel use	Transport	Process	Total
COD	22	2	86	89,500	89,600
BOD	6	-	6	4,790	4,800
Acid (H+)	4	-	0	1	5
Al+compounds as Al	0	-	0	3	3
Ammonium compounds as NH4	7	-	2	1	11
AOX	0	-	0	15	15
As+compounds as As	-	-	0	0	0
BrO3--	0	-	0	0	0
Ca+compounds as Ca	0	-	0	302	302
Cd+compounds as Cd	-	-	0	-	0
Cl-	10	-	1,010	41,200	42,200
ClO3--	0	-	0	2	2
CN-	0	-	0	0	0
CO3--	-	-	3	7	10
Cr+compounds as Cr	0	-	0	0	0
Cu+compounds as Cu	0	-	0	0	0
Detergent/oil	0	-	2	4	7
Dichloroethane (DCE)	0	-	0	0	0
Dioxin/furan as Teq	-	-	0	-	0
Dissolved chlorine	0	-	0	0	0
Dissolved organics (non-HC)	9	-	0	1	10
Dissolved solids not specified	2	-	10	89	101
F-	0	-	9	0	9
Fe+compounds as Fe	0	-	2	31	33
Hg+compounds as Hg	0	-	0	0	0
Hydrocarbons not specified	1	1	2	501	505
K+compounds as K	0	-	0	3	3
Metals not specified elsewhere	0	-	0	76	76
Mg+compounds as Mg	0	-	0	3	3
Mn+compounds as Mn	-	-	0	0	0
Na+compounds as Na	4	-	23	1,900	1,930
Ni+compounds as Ni	0	-	0	0	0
NO3-	0	-	0	2,860	2,860
Organo-chlorine not specified	0	-	0	0	0
Organo-tin as Sn	-	-	0	-	0
Other nitrogen as N	0	-	0	6,440	6,440
Other organics not specified	0	-	0	0	0
P+compounds as P	0	-	0	62	62
Pb+compounds as PB	0	-	0	0	0
Phenols	0	-	0	0	0
S+sulphides as S	0	-	0	7	7
SO4--	0	-	8	9,430	9,440
Sr+compounds as Sr	-	-	0	0	0
Suspended solids	1,420	-	3,990	594,000	599,000
TOC	0	-	23	3,690	3,710
Vinyl chloride monomer	0	-	0	0	0
Zn+compounds as Zn	0	-	0	0	0

Table 24A. Generation of solid waste (in milligrams) resulting from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1000 bags. Totals may not agree because of rounding.

Solid waste (mg)	Fuel prod'n	Fuel use	Transport	Process	Total
Construction waste	0	-	0	0	0
Inert chemical	0	-	0	5	5
Metals	0	-	0	822	822
Mineral waste	1,110	-	26,500	405,000	433,000
Mixed industrial	-12,800	-	1,100	2,620	-9,080
Municipal solid waste	-130,000	-	-	205,000	75,000
Paper	0	-	0	0	0
Plastic containers	0	-	0	-	0
Plastics	0	-	0	1,580	1,580
Putrescibles	0	-	7	1	8
Regulated chemicals	18,400	-	4,830	133	23,400
Slags/ash	308,000	660	10,300	2,690,000	3,009,000
Tailings	27	-	15,900	284	16,300
Unregulated chemicals	14,000	-	0	82,400	96,400
Unspecified refuse	15,100	-	0	171,700	186,800
Waste returned to mine	731,000	-	980	108	732,100
Waste to compost	-	-	-	25,400	25,400
Waste to incinerator	0	-	12	67	80
Waste to recycle	0	-	0	32,500	32,500
Wood waste	0	-	0	6,370	6,370
Wood pallets to recycling	0	-	0	812,700	812,700

Table 24B. Generation of solid waste (in milligrams) resulting from the COMPOSTABLE PLASTIC bag LCA. Based on consumer use & collection of 1500 bags. Totals may not agree because of rounding.

Solid waste (mg)	Fuel prod'n	Fuel use	Transport	Process	Total
Construction waste	0	-	0	0	0
Inert chemical	0	-	0	6	6
Metals	0	-	0	1,230	1,230
Mineral waste	1,660	-	39,800	608,000	649,000
Mixed industrial	-19,200	-	1,650	3,940	-13,600
Municipal solid waste	-195,000	-	-	308,000	113,000
Paper	0	-	0	0	0
Plastic containers	0	-	0	-	0
Plastics	0	-	0	2,380	2,380
Putrescibles	0	-	11	<1	11
Regulated chemicals	27,600	-	7,250	199	35,100
Slags/ash	462,000	985	15,500	4,035,000	4,510,000
Tailings	40	-	23,900	427	24,400
Unregulated chemicals	20,900	-	52	124,000	145,000
Unspecified refuse	22,600	-	0	258,000	280,000
Waste returned to mine	1,097,000	-	1,470	162	1,098,000
Waste to compost	-	-	-	38,000	38,000
Waste to incinerator	0	-	18	101	120
Waste to recycle	0	-	0	48,800	48,800
Wood waste	0	-	0	9,550	9,550
Wood pallets to recycling	0	-	0	1,220,000	1,220,000

Final Disposal Solid Waste Options: Recycling, Combustion with Energy Recovery, Landfill and Composting

Recycling

A major goal of recycling is to reduce the generation of solid waste. The bag making process for grocery bags generates paper and plastic waste. The majority of this waste, known as mill waste, is recycled internally. Therefore, in this study BCAL treated mill waste as a closed loop recycling effort that returned the waste to the production process.

All of the grocery bags are recyclable to other paper and plastic products. EPA data from 2005 show that 21% of the kraft paper grocery bags are recycled and 5.2 % of the plastic grocery bags are recycled. The allocation decision for these recycled materials is that the recycled materials are not burdened with any inputs or outputs associated with their previous manufacture, use, disposal prior to recycling.

BCAL used this allocation approach, and treated the recycled materials as diverted waste. Diverted waste, like raw materials, are burdened with their intrinsic feedstock value and are subsequently burdened with the resource use, energy consumption, and environmental releases associated with their collection, cleaning and reprocessing, use, and disposal. Therefore, the inherent feedstock energy value of the recycled material is assigned to the diverted waste.

With respect to the degradable plastic bags, BCAL assumed that initially the same rate that applies to recycling of standard plastic bags (5.2%) would be appropriate for the rate sent to composting. This reflects a conservative approach using only data that currently reflect consumer behavior with regard to plastic bags. It is expected that the percentage of degradable plastic bags sent to composting will actually be higher once they are made available and collection can occur within municipalities, making it easier for the general consumer to send these bags through a different route of disposal. Recycling of plastic bags is currently low. This may be for a number of reasons, not the least of which appears to be the lack of infrastructure and poor consumer awareness about the inherent recycleability of plastic bags.

Solid Waste Combustion With Energy Recovery

In previous years, a controlled burning process called combustion or incineration was used solely to reduce volume of solid waste. However, energy recovery became more prevalent in the 1980s. Therefore, today, most of the municipal solid waste combustion in the US incorporates recovery of energy. EPA data from 2005 show that 13.6% of MSW was combusted with energy recovery.

The gross calorific values for the various grocery bags are estimated as follows:

For kraft paper bags	17.7 MJ/kg
For recyclable plastic bag	40.0 MJ//kg
For degradable plastic bag	19.6 MJ/kg

These materials are used as fuels in the waste to energy plants, however the thermal efficiencies for mass-burn WTE plants varies from 15% to 23% in the newer plants.[6] This study used 23% thermal efficiency for energy recovery.

Assuming complete combustion, the resulting estimated CO2 emissions are:
For kraft paper bags 1,650,000 mg/kg paper bag
For recyclable plastic bags 3,150,000 mg/kg recyclable plastic bag
For degradable plastic bags 1,360,000 mg/kg degradable plastic bag

The recovered energy (23% thermal efficiency) is as follows:
For kraft paper bags 4.07 MJ/kg paper bag
For recyclable plastic bags 9.20 MJ/kg recyclable plastic bag
For degradable plastic bags 4.51 MJ/kg degradable plastic bag

Therefore, using the above information, the following table is prepared on the basis of 1000 grocery bags and shows the recovered energy and resulting carbon dioxide emissions when 13.6% of the 1000 grocery bags are combusted with energy recovery.

Table 25. Recovered energy (MJ) and resulting carbon dioxide emissions (mg) when 13.6% of the 1000 grocery bags are combusted with energy recovery.

	Kraft Paper Bag	Recyclable Plastic Bag	Degradable Plastic Bag
Recovered energy	28.7 MJ	7.2 MJ	9.7 MJ
CO2 emissions	11,640,000 mg	2,150,000 mg	2,920,000 mg

Table 25 shows that the kraft paper bag has the highest recovered energy and the highest CO2 emissions. The recyclable and compostable plastic bags have significantly lower recovered energy and CO2 emissions.

Solid Waste to Landfill

A landfill has various phases of decomposition. Initially, aerobic decomposition will take place where oxygen is consumed to produce carbon dioxide gas and other by-products. During the first phase of anaerobic decomposition, carbon dioxide is the principal gas generated. As anaerobic decomposition proceeds toward the second phase, the quantity of methane generated increases until the methane concentration reaches 50% to 60%. The landfill will continue to generate methane at these concentrations for 10 or 20 years, and possibly longer[7].

Methane emissions from landfills in the United States were estimated at 8.0 million metric tons in 2001. In addition, 2.5 million tons were recovered for energy use and 2.4 million tons were recovered and flared. Therefore, more than 60% of the methane produced in landfills is not recovered.[8]

The precise fate of paper deposited in a landfill site is unknown. Paper may decompose entirely in a short space of time or it may remain intact for long periods.[9] This depends on a variety of factors such as temperature, pH, the presence of bacteria and nutrients, the composition of the waste and the form of the paper-shredded paper is much more likely to decompose than is a whole telephone book. To account for this variability, two scenarios were used to calculate emissions associated with the disposal of paper bags (both adjustment for 40% of the recovered methane noted above). The first scenario is a worst-case scenario that follows the basic decomposition reaction for cellulose and the second scenario is one that estimates carbon sequestration for paper in MSW landfills.

Scenario 1 for Paper Bags

The basic decomposition reaction for cellulose is well known and follows the form of:

$$C_6H_{10}O_5 + H_2O = 3CH_4 + 3CO_2 \qquad (1)$$

It is therefore expected that only one half of the carbon present in kraft paper bags will result in methane formation during decomposition. Typically carbon represents 45% of the mass of paper. Thus, the carbon content of 1 kg of paper will be 0.45 kg. That proportion giving rise to methane, assuming 100 % decomposition, would then be 0.225 kg. Based on this, the mass of methane produced would be 0.30 kg and the corresponding mass of the coproduct carbon dioxide would be 0.83 kg.

Scenario 2 for Paper Bags

Although cellulose decomposition in landfill is well documented, there remains significant uncertainty in the maximum extent of cellulose decomposition that can be realized under landfill conditions. Several studies indicate that significant carbon sequestration occurs in landfills because of the limited degradation of wood products. In one study[10] [a] carbon storage factor (CSF) was calculated that represented the mass of carbon stored (not degraded) per initial carbon mass of the component. For the following MSW paper refuse components the CSF was calculated: old newsprint = 0.42 kg C sequestered, coated paper = 0.34 kg C sequestered, and old corrugated = 0.26 kg C sequestered.

For this scenario the partial decomposition that the paper bags go through is assumed to be aerobic or the initial anaerobic phase, resulting principally in carbon dioxide emissions. In this scenario, we have assumed that the paper bags are similar to old corrugated, and therefore have assigned the same value of 0.26 kg C sequestered. Given that 0.26 kg of the kraft paper bag is assumed to be sequestered, 0.74 kg of the kraft paper bag results in carbon dioxide emissions of 1.23 kg.

Recyclable plastic bags are not considered to degrade in landfills, suggesting that all the inherent feedstock energy and emissions will be sequestered. Therefore, there are no carbon dioxide or methane emissions associated with the recyclable plastic bags sent to landfills.

Many types of biodegradable polymers are available to degrade in a variety of environments, including soil, air, or compost. The biodegradable products degrade under aerobic conditions to carbon dioxide and water in the presence of oxygen. The biodegradable, compostable plastic bags in this study are made from a blend of Ecoflex and PLA. Ecoflex is made from aliphatic-aromatic copolyester blended with equal amounts of starch. According to information provided by BASF, Ecoflex meets the requirements for biodegradable polymer classification based on European, US, and Japanese standards because Ecoflex can be degraded by micro-organisms.[11] PLA is a biodegradable polymer made from corn and is converted completely to carbon dioxide and water by micro-organisms. In addition, compostable plastic bags have been found to degrade as designed within an allowable timeframe in appropriate composting facilities[13]. In composting facilities, decomposition of biodegradable plastic bags made from a blend of Ecoflex and PLA are expected to release primarily carbon dioxide emissions and water. However, if sent to a landfill, biodegradable plastic will either not degrade at all, or may follow similar pathways as paper bags (a combination of both aerobic and anaerobic degradation). BCAL treated these bags in both ways in this study to examine all possibilities.

Solid Waste Composting

The biodegradable, compostable plastic bags in this study have demonstrated biodegradation in several standardized tests in several countries. Ecoflex and PLA meet US, European, Australian, and Japanese standards by degrading in 12 weeks under aerobic conditions in a compost environment and by breaking down to carbon dioxide and water. The extent of the degradation for Ecoflex was 2 to 6 months in compost depending upon temperature, and for PLA was 1 to 3 months in compost depending upon temperature. [11] Therefore, in the composting environment, decomposition of biodegradable plastic bags made from a blend of Ecoflex and PLA is expected to degrade over time with the release primarily of carbon dioxide emissions and water.

LCA Calculations of Environmental Impacts

As noted under the section on LCA methodology, life cycle assessment modeling allows an examination of specific problems as well as comparisons to determine if there are any serious side effects to any of the systems under study. In every system there are multiple environmental parameters to be addressed scaling from global to local issues, and no single solution is likely to address all of the issues simultaneously. In addition, almost every change to a system creates trade-offs, and it is the identification of these trade-offs that is important when trying to determine the best solution for any given problem.

To reiterate, a life cycle assessment can:

1. Quantify those parameters likely to be responsible for environmental effects (the inventory component of life cycle analysis).
2. Identify which parameters are likely to contribute to a specific environmental problem (characterization or interpretation phase of impact assessment). An

example would be identifying that carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are greenhouse gases.

3. Aggregate the parameters relating to a specific problem (the valuation or interpretation phase of impact assessment). An example would be producing carbon dioxide equivalents for the components of greenhouse gases.

The LCA calculations provide a compilation of information from which the user can address specific problems such as the conservation of fossil fuels, global warming, acid rain, and municipal solid waste. In addition, the user also is able to determine what trade-offs exist between systems and to examine the specific parameters which are likely to contribute to these problems. In so doing, the user can strive to achieve the optimum reduction in each parameter because of a better understanding of how these parameters change in association with each grocery bag system.

GLOBAL WARMING

One important issue that is currently being addressed using LCA studies is an examination of the contribution that industrial systems make to climate change. The work of the Intergovernmental Panel on Climate Change (IPCC)[12] provides a framework for aggregating data on those air emissions that are thought to be significant contributors to global warming. The aggregated effect of any system can be summarized as a parameter known as Global Warming Potential (GWP) or carbon dioxide equivalent. Any gaseous emission that is thought to contribute to global warming is assigned a value equal to the equivalent amount of CO_2 that would be needed to produce the same effect. Multiplying each gaseous emission by its CO_2 equivalent allows the separate effects of different emissions to be summed to give an overall measure of global warming potentials.

The major greenhouse gases of importance in this eco-profile are carbon dioxide, methane and nitrous oxide. The results tables provided previously (see Section on LCA Results) showed the global warming impacts (with carbon dioxide equivalents) up to the collection of the grocery bags.

The following table estimates the global warming impacts just from the collection and disposal of the grocery bags.

As discussed previously, two scenarios will be considered for the kraft paper bags, the first is a worst-case scenario that follows the basic decomposition reaction for cellulose and the second scenario is one that estimates carbon sequestration for paper in MSW landfills.

The recyclable plastic bags will not degrade in the landfill; all the inherent feedstock energy and emissions will be sequestered. Therefore, there are no carbon dioxide emissions from recyclable plastic bags in landfills.

In the landfill, decomposition of biodegradable plastic bags made from a blend of Ecoflex and PLA is expected to degrade over time with the release primarily of carbon dioxide emissions and water.

Table 26A. Greenhouse gas emissions. 20-year carbon dioxide equivalents (in milligrams) resulting from the disposal of 1000 grocery bags.

Disposal process	Paper bag with “worst case scenario” of methane emissions	Paper bag with “sequestered scenario” of carbon dioxide emissions	Recyclable plastic bag	Degradable plastic bag With 100% aerobic decomposition in landfill	Degradable plastic bag with 50% aerobic & 50% anaerobic decomposition in landfill (using the same pathway as described for paper bags)
Recycling	21% recycled & burden is transferred	21% recycled & burden is transferred	5.2% recycled & burden is transferred	5.2% recycled to composting & burden is transferred	5.2% recycled to composting & burden is transferred
Incineration with energy recovery 13.6%	11,640,000	11,640,000	2,150,000	2,920,000	2,920,000
Landfill 65.4% paper, 81.2% plastic	412,000,000	41,300,000	0	17,400,000	129,400,000
Total disposal related emissions	423,640,000	52,940,000	2,150,000	20,320,000	132,320,000

Table 26A shows that after disposal, the recyclable plastic bag has the lowest greenhouse gas emissions. The paper bag with the “sequestered scenario” has more than 15 times the greenhouse gas emissions of the recyclable plastic bag. The paper bag with the “worst-case scenario” has more than 200 times the greenhouse gas emissions of the recyclable plastic bag. The degradable plastic bag has more than 9 times the greenhouse gas emissions of the recyclable plastic bag.

Table 26B. Greenhouse gas emissions. 20-year carbon dioxide equivalents (in milligrams) resulting from the disposal of 1000 kraft paper grocery bags and 1500 recyclable plastic and degradable plastic grocery bags.

Disposal process	Paper bag with “worst case scenario” of methane emissions	Paper bag with “sequestered scenario” of carbon dioxide emissions	Recyclable plastic bag	Degradable plastic bag With 100% aerobic decomposition in landfill	Degradable plastic bag with 50% aerobic & 50% anaerobic decomposition in landfill
Recycling	21% recycled & burden is transferred	21% recycled & burden is transferred	5.2% recycled & burden is transferred	5.2% recycled to composting & burden is transferred	5.2% recycled to composting & burden is transferred
Incineration with energy recovery 13.6%	11,640,000	11,640,000	3,230,000	4,380,000	4,380,000
Landfill 65.4% paper, 81.2% plastic	412,000,000	41,300,000	0	26,100,000	194,000,000
Total disposal related emissions	423,640,000	52,940,000	3,230,000	30,500,000	198,000,000

Table 26B shows that even using 1.5 plastic bags to 1 paper bag, after disposal, the recyclable plastic bag has the lowest greenhouse gas emissions. The paper bag at a 1 to 1.5 use ratio, with the “sequestered scenario,” has more than 10 times the greenhouse gas emissions of the recyclable plastic bag. The paper bag with the “worst-case scenario” has more than 130 times the greenhouse gas emissions of the recyclable plastic bag. The degradable plastic bag has more than 9 times the greenhouse gas emissions of the recyclable plastic bag with the 100% aerobic decomposition and more than 60 times the greenhouse gas emissions of the recyclable plastic bag with the 50% aerobic decomposition/50% anaerobic decomposition.

Table 27A. Carbon dioxide equivalents (in milligrams) resulting from all operations just prior to the disposal of 1000 grocery bags.

	Recyclable and Recycled Paper bag* (from Table 6B)	Recyclable plastic bag (from Table 14B)	Degradable plastic bag (from Table 22B)
20 year CO2 eq.	23,710,000 mg	19,200,000 mg	89,000,000 mg

*It should be noted that these emissions include the “credit” when carbon dioxide was absorbed during tree growing.

Table 27A shows that from all operations just prior to disposal, the resulting CO2 equivalents are more than 20% greater for the paper bag compared to the recyclable plastic bag. From all operations just prior to disposal, the resulting CO2 equivalents for the degradable plastic bag are the highest about 4 times greater than the recyclable plastic bag.

Table 27B Carbon dioxide equivalents (in milligrams) resulting from all operations just prior to the disposal of 1000 kraft paper grocery bags and 1500 recyclable plastic and degradable plastic grocery bags.

	Recyclable and Recycled Paper bag* (from Table 6B)	Recyclable plastic bag (from Table 14B)	Degradable plastic bag (from Table 22B)
20 year CO2 eq.	23,710,000 mg	28,800,000 mg	134,000,000 mg

*It should be noted that these emissions include the “credit” when carbon dioxide was absorbed during tree growing.

Table 27B shows that from all operations just prior to disposal, the resulting CO2 equivalents are more than 20% greater for the recyclable plastic bag compared to the paper bag. From all operations just prior to disposal, the resulting CO2 equivalents for the degradable plastic bag are the highest about 4 times greater than the recyclable plastic bag and 5 times greater than the paper bag.

Now, adding the greenhouse gas emissions from tables 26 and 27 the total LCA cradle-to-grave greenhouse gas emissions for the production, use, and disposal of 1000 grocery bags are given in Table 28.

Table 28A. Total LCA cradle-to-grave CO2 equivalents (in milligrams) for the production, use, and disposal of 1000 grocery bags:

	Paper bag with “worst-case scenario” of methane emissions	Paper bag with “sequestered scenario” of carbon dioxide emissions	Recyclable plastic bag	Degradable plastic bag With 100% aerobic decomposition in landfill	Degradable plastic bag with 50% aerobic & 50% anaerobic decomposition in landfill
20 year CO2 eq	447,350,000	76,650,000	21,350,000	109,300,000	221,300,000
100 year CO2 eq	202,200,000	65,490,000	18,850,000	99,300,000	134,800,000
500 year CO2 eq	90,410,000	60,910,000	17,850,000	87,320,000	92,100,000

Table 28A shows that the recyclable plastic bag has the lowest the total cradle-to-grave CO2 equivalents. The paper bag with the “sequestered scenario” has more than 3.5 times the total cradle-to-grave CO2 equivalents of the recyclable plastic bag. The paper bag with the “worst-case scenario” has more than 20 times the total cradle-to-grave CO2 equivalents of the recyclable plastic bag. The degradable plastic bag has more than 5 times the total cradle-to-grave CO2 equivalents of the recyclable plastic bag.

Table 28B. Total LCA cradle-to-grave CO_2 equivalents (in milligrams) for the production, use, and disposal of 1000 kraft paper grocery bags and 1500 recyclable plastic and degradable plastic grocery bags.

	Paper bag with "worst-case scenario" of methane emissions	Paper bag with "sequestered scenario" of carbon dioxide emissions	Recyclable plastic bag	Degradable plastic bag With 100% aerobic decomposition in landfill	Degradable plastic bag with 50% aerobic & 50% anaerobic decomposition in landfill
20 year CO2 eq	447,350,000	76,650,000	32,030,000	164,000,000	332,000,000
100 year CO2 eq	202,200,000	65,490,000	28,300,000	149,000,000	202,000,000
500 year CO2 eq	90,410,000	60,910,000	26,800,000	131,000,000	138,000,000

Table 28B shows that even using 1.5 plastic bags to 1 paper bag, the recyclable plastic bag has the lowest the total cradle-to-grave CO2 equivalents. The paper bag, at a 1 to 1.5 use ratio, with the "sequestered scenario," has about 2.3 times more total cradle-to-grave CO2 equivalents of the recyclable plastic bag, depending upon the time horizon. The paper bag with the "worst-case scenario" has more than 20 times the total cradle-to-grave CO2 equivalents of the recyclable plastic bag. The degradable plastic bag has more than 5 times the total cradle-to-grave CO2 equivalents of the recyclable plastic bag.

STRATOSPHERIC OZONE DEPLETION

The stratospheric ozone layer occurs at an altitude of between 10-40 km. The maximum generation of ozone (O_3) occurs at the outer layer, where oxygen molecules (O_2) react with atomic oxygen. The presence of other compounds, particularly halogenated compounds, promotes the decomposition of this ozone in the presence of strong ultra-violet radiation.

In this study there were no identified ozone depleting chemicals associated with the bag systems studied, and therefore no contributions to stratospheric ozone depletion.

ACID RAIN

The production of acid rain in the northeastern United States is recognized as a regional problem. Acid rain results when sulfur and nitrogen oxides and their transformation products return from the atmosphere to the earth's surface. The major source of acid rain is the emission of these pollutants from coal powered electricity generating plants.

The following data were extracted from the results tables. There are no data available for SOX and NOX emissions after disposal.

Table 29A. Acid rain emissions (in milligrams of SO_2 and NO_2) resulting from all operations just prior to disposal 1000 grocery bags.

Acid rain emissions mg	Paper bag	Recyclable plastic bag	Degradable plastic bag
SOX	579,000 mg	50,500 mg	275,000 mg
NOX	264,000 mg	45,400 mg	304,000 mg

Table 29A shows that the recyclable plastic bag has the least SOX and NOX emissions. The paper bag has more than 10 times the SOX emissions compared with the recyclable plastic bag and more than 5 times the NOX emissions compared with the recyclable plastic bag. The degradable plastic bag has more than 5 times the SOX and NOX emissions compared with the recyclable plastic bag.

Table 29B. Acid rain emissions (in milligrams of SO_2 and NO_2) resulting from all operations just prior to disposal for 1500 recyclable plastic bags and degradable plastic grocery bags.

Acid rain emissions mg	Paper bag	Recyclable plastic bag	Degradable plastic bag
SOX	579,000 mg	75,800 mg	413,000 mg
NOX	264,000 mg	68,100 mg	456,000 mg

Table 29B shows that even using 1.5 plastic bags to 1 paper bag, the recyclable plastic bag has the least SOX and NOX emissions. The paper bag, at a 1 to 1.5 use ratio, has more than 7 times the SOX emissions compared with the recyclable plastic bag and almost 4 times the NOX emissions compared with the recyclable plastic bag. The degradable plastic bag has more than 5 times the SOX and NOX emissions compared with the recyclable plastic bag.

MUNICIPAL SOLID WASTE

Another widespread environmental issue concerns the generation and disposal of municipal solid waste. The mineral wastes from mining, the slags and ash wastes from oil and gas production and utility coal combustion, and regulated chemical wastes are generally managed by regulation and permits that exclude these wastes from the municipal solid waste stream. The type of wastes in mixed industrial wastes can contribute to the municipal solid waste problem. If, as in this study, there is an interest in focusing on the municipal solid waste problem, the results on mineral wastes, slags & ash, and regulated chemicals can be ignored. Selecting only the solid waste resulting from just the disposal of grocery bags in landfill, one can prepare the following table 30A considering disposal of 1000 grocery bags and table 30B considering disposal of 1000 kraft paper grocery bags and 1500 recyclable plastic and degradable plastic grocery bags. The table reflects the waste that is landfilled as 65.4% paper bags and 81.2% plastic bags.

Table 30A. The municipal solid waste (in mg) resulting from just the disposal of grocery bags in landfill. Based on 1000 grocery bags but only 65.4% of paper bags are landfilled and 81.2% of plastic bags are landfilled.

	Paper bag	Recyclable plastic bag	Degradable plastic bag
Municipal solid waste mg	33,900,000	4,690,000	12,800,000

Table 30A shows that the recyclable plastic bag has the least municipal solid waste. The paper bag has more than 7 times the municipal solid waste compared with the recyclable plastic bag. The degradable plastic bag has almost 3 times the municipal solid waste compared with the recyclable plastic bag.

Table 30B. The municipal solid waste (in mg) resulting from just the disposal of grocery bags in landfill. Based on 1000 kraft paper grocery bags but only 65.4% of paper bags are landfilled and 1500 plastic grocery bags of which 81.2% of plastic bags are landfilled.

	Paper bag	Recyclable plastic bag	Degradable plastic bag
Municipal solid waste mg	33,900,000	7,035,000	19,200,000

Table 30B shows that even using 1.5 plastic bags to 1 paper bag, the recyclable plastic bag has the least municipal solid waste. The paper bag, at a 1 to 1.5 use ratio, has almost 5 times the municipal solid waste compared with the recyclable plastic bag. The degradable plastic bag has almost 3 times the municipal solid waste compared with the recyclable plastic bag.

CONSERVATION OF FOSSIL FUELS

Conservation problems are concerned with the depletion and possible exhaustion of raw materials and fuels. With continued use, the finite supply of raw materials, and especially fossil fuels will one day be exhausted. The conservation of fossil fuels: coal, oil ,and natural gas is an important global environmental issue. It is therefore important to ensure that these resources are used with the maximum efficiency and the minimum of waste.

Table 31A. The gross fossil fuels and feedstocks, expressed as energy (MJ) required for the production, use, and disposal of 1000 grocery bags.

Energy in MJ	Paper bag	Recyclable plastic bag	Degradable plastic bag
Coal	324	65	161
Oil	207	206	353
Gas	391	186	705
Totals	922	457	1,219

Table 31A shows that the recyclable plastic bag uses the least fossil fuels and feedstocks. The paper bag uses more than 2 times the fossil fuels and feedstocks compared with the recyclable plastic bag. The degradable plastic bag used more than 2 1/2 times the fossil fuels and feedstocks compared with the recyclable plastic bag.

Table 31B. The gross fossil fuels and feedstocks, expressed as energy (MJ) required for the production, use, and disposal of 1000 kraft paper grocery bags and 1500 recyclable plastic and degradable plastic grocery bags.

Energy in MJ	Paper bag	Recyclable plastic bag	Degradable plastic bag
Coal	324	98	242
Oil	207	309	530
Gas	391	279	1,058
Totals	922	686	1,830

Table 31B shows that even using 1.5 plastic bags to 1 paper bag, the recyclable plastic bag uses the least fossil fuels and feedstocks. The paper bag, at a 1 to 1.5 use ratio, uses 34% more fossil fuels and feedstocks compared with the recyclable plastic bag. The degradable plastic bag used more than 2 1/2 times the fossil fuels and feedstocks compared with the recyclable plastic bag.

LOCAL & REGIONAL GRID ELECTRICITY USE

The US recently has experienced severe problems related to its local and regional grid electricity. Because of these recent “blackouts,” “brownouts,” and electricity interruptions, the need for appropriate conservation measures can be argued.

Table 32A. The electrical energy (MJ) required for the production, use, and disposal of 1000 grocery bags.

	Paper bag	Recyclable plastic bag	Degradable plastic bag
Electrical energy MJ	649	148	325

Table 32A shows that the recyclable plastic bag uses the least electrical energy. The paper bag uses more than 4 times the electrical energy compared to the recyclable plastic bag. The degradable plastic bag used more than 2 times the electrical energy compared with the recyclable plastic bag.

Table 32B. The electrical energy (MJ) required for the production, use, and disposal of 1000 kraft paper grocery bags and 1500 recyclable plastic and degradable plastic grocery bags.

	Paper bag	Recyclable plastic bag	Degradable plastic bag
Electrical energy MJ	649	222	488

Table 32B shows that even using 1.5 plastic bags to 1 paper bag, the recyclable plastic bag uses the least electrical energy. The paper bag, at a 1 to 1.5 use ratio, uses almost 3 times the electrical energy compared with the recyclable plastic bag. The degradable plastic bag used more than 2 times the electrical energy compared with the recyclable plastic bag.

WATER USE & PUBLIC SUPPLY

Parts of the US continue to be plagued by periodic drought conditions. During these times, laws and regulations concerning water conservation are enforced. Since public water supply issues have been identified as a problem, the following table has been prepared to compare public water supply used for the production, use, and disposal of 1000 grocery bags.

Table 33A. Public water supply (in mg) used for the production, use, and disposal of 1000 grocery bags.

	Paper bag	Recyclable plastic bag	Degradable plastic bag
Public water supply (in mg)	3,895,000,000	31,150,000	2,560,000,000

Table 33A shows that the recyclable plastic bag uses the least public water supply. The paper bag uses more than 125 times the public water supply compared with the recyclable plastic bag. The degradable plastic bag used more than 80 times the public water supply compared with the recyclable plastic bag.

Table 33B. Public water supply (in mg) used for the production, use, and disposal of 1000 kraft paper grocery bags and 1500 recyclable plastic and degradable plastic grocery bags.

	Paper bag	Recyclable plastic bag	Degradable plastic bag
Public water supply	3,895,000,000	46,700,000	3,840,000,000

(in mg)			

Table 33B shows that even using 1.5 plastic bags to 1 paper bag, the recyclable plastic bag uses the least public water supply. The paper bag, at a 1 to 1.5 use ratio, uses more than 80 times the public water supply compared with the recyclable plastic bag. The degradable plastic bag used more than 80 times the public water supply compared with the recyclable plastic bag.

SUMMARY AND CONCLUSIONS

Recent efforts by legislators to ban traditional plastic bags on the basis of environmental impact have reignited the debate surrounding single-use grocery bags, and whether there are any environmental trade-offs in switching from bags made with polyethylene to bags made from alternative materials.

This life cycle assessment was commissioned to examine the overall environmental impacts associated with the typical single-use polyethylene plastic grocery bag, compared with grocery bags made from compostable plastic resin and grocery bags made from 30% recycled paper.

Life cycle assessment is a useful analytical tool because it allows for the examination of an entire production system from cradle to grave, thus examining the full range (global, regional, and local impacts) of environmental issues at once rather than examining individual components of a system or individual products or processes. This broad picture analysis is important because environmental effects range from global (greenhouse gases), to regional (acid rain/solid waste) or local (toxic releases) impacts. And while there often is excellent information on local environmental effects, few complete data sets are available to understand the contributions production systems are making to global and regional environmental problems.

These study results confirm that the standard polyethylene grocery bag has significantly lower environmental impacts than a 30% recycled content paper bag. This supports conclusions drawn from a number of other studies looking at similar systems.[14, 15, 16] In addition, this report also shows that the typical polyethylene grocery bag has fewer environmental impacts than a compostable plastic grocery bag made from a blend of EcoFlex (BASF), polylactic acid, and calcium carbonate, when compared on a 1:1 basis, as well as when the number of bags is adjusted for carrying capacity so that the comparison is 1.5:1. Surprisingly, the trend is the same for most of the individual categories of environmental impacts. No one category showed environmental impacts lower for either the compostable plastic bag or the paper bag.

This study did not examine the impacts associated with reusable cloth bags, so no comparison was made between the cloth bags and single-use polyethylene plastic bags. In other studies, however, cloth bags were shown to reduce environmental impacts if consumers can be convinced to switch. The problem is that there are few examples where entire cities, counties, or countries have been successful in changing consumer behavior from the convenience of using bags provided by retail establishments to bringing their own bags to the store each time they shop. There is no question that a percentage of consumers do, and will use reusable cloth grocery bags, but the vast majority of consumers still appear to use the freely available bags provided by retail establishments. So, if consumer behaviors are not appearing to change, banning one type of single-use bag will simply mean that it is replaced by another type of single-use bag.

Given the above-stated assumption, it is clear that the replacement bags will either be compostable plastic bags or paper bags, as proposed legislation tends to stipulate these as the preferred alternatives. But can these alternative materials meet the legislative objectives, which often include: the reduction of litter, the need to reduce dependence on fossil fuels, and the need to reduce solid wastes? Taking the latter two objectives first, one can use the LCA results in this report to see if the above stated objectives are being met.

In the case of reducing dependence on overall energy, it is clear (see Table 34) that neither the life cycle of compostable bag nor paper bag provides a reduction in overall energy use. The standard polyethylene plastic grocery bag uses between 1.8 and 3.4 times less energy than the compostable and paper bag systems, respectively.

Table 34. Gross Energy by Activity (MJ)

	Fuel prod'n (total)	Fuel use (total)	Transport (total)	Feedstock (total)	Total
Paper Bag (1000 bags)	493	1105	34	991	2622
Compostable Plastic Bag (1000 bags)	265	659	38	418	1380
Compostable Plastic Bag (1500 bags)	398	988	57	627	2070
Polyethylene Plastic Bag (1000 bags)	106	114	11	279	509
Polyethylene Plastic Bag (1500 bags)	159	171	16	418	763

Table 35 demonstrates that in terms of fossil fuel use, including oil, the compostable plastic bag system does not provide any benefit. The compostable plastic bag system appears to use more oil than either of the other two bag systems, varying from 1.7 to 2.57 times more oil than either the plastic bag or paper bag systems, respectively. The paper bag system would appear to be able to provide a slight improvement, but only if the plastic bag system actually uses 1.5 bags for every 1 bag in the paper system. If this assumption cannot be supported, then the paper bag system would not provide even a slight advantage.

Table 35. Gross Fossil Fuel Use (kg)					
	Paper Bag (1000 bags)	Compostable Plastic Bag (1000 bags)	Compostable Plastic Bag (1500 bags)	Polyethylene Plastic Bag (1000 bags)	Polyethylene Plastic Bag (1500 bags)
Coal	11.2	5.8	8.7	2.3	3.4
Oil	4.6	7.8	11.8	4.6	6.9
Gas	7.4	14.0	21.0	3.1	4.6

These results may appear to some to be counterintuitive, but both compostable plastic and paper bags require more material per bag in their manufacture. This results in greater use of fuels in the extraction and transport of raw materials for the manufacture of the bags, as well as greater energy in bag manufacturing and greater fuel use in the transport of the finished product from the manufacturer to retail establishments. Although standard polyethylene plastic bags are made from oil, the added requirements of manufacturing energy and transport for the compostable and paper bag systems far exceed the raw material use in the standard plastic bag system.

The results of this study also show that the standard polyethylene single-use plastic grocery bag's contribution to the solid waste stream is far lower than either the paper bag system or the compostable bag system. This is not surprising considering both the compostable bag and paper bag systems require more material per bag. The increase in solid wastes has become an important global issue as populations multiply and developing countries become wealthier, consuming more material goods. Currently, more land is being devoted to the disposing of solid wastes, and the lack of proper containment in solid waste facilities is causing problems in terms of soil contamination and water pollution.

Table 36. Municipal Solid Waste (kg)				
Paper Bag (1000 bags)	Compostable Plastic Bag (1000 bags)	Compostable Plastic Bag (1500 bags)	Polyethylene Plastic Bag (1000 bags)	Polyethylene Plastic Bag (1500 bags)
33.9	12.8	19.2	4.7	7.0

This study was not designed to address the issue of litter, so no specific calculations were conducted on the effect of the various bag systems on litter. However, there are some interesting points that can be made with regard to meeting the objective of reducing litter by switching to alternative materials in the grocery bag system. The summary of results discussed above on energy use and solid waste already illustrate that reducing litter through a change in the grocery bag system will lead to greater use in energy and greater amounts of solid wastes. Those who believe that this is an acceptable trade-off must also understand that there are additional, and perhaps far more serious, environmental impacts that will result if plastic bags are supplanted by either compostable plastic bags or paper.

One of these serious environmental impacts is global warming. The study showed that switching from single-use polyethylene plastic grocery bags to either paper or compostable plastic grocery bags may increase the emission of greenhouse gases and therefore contribute to global warming (See Table 37). Based on these results, it appears that the trade-off for reducing litter is an increase in global warming, which if not curbed, is expected to cause problems for decades and to affect marine, freshwater, and terrestrial habitats, and species globally. If one of the major concerns about litter is its accumulation in marine habitats and its negative effect on sea life, it would hardly seem justified to address the effects of litter with a grocery bag system that can cause significant harm to not only the same habitats, but to all other habitats as well.

Table 37. Global Warming Potential (CO2 Equivalents in tons)				
	Paper bag with "sequestered scenario" of carbon dioxide emissions (1000 bags)	Compostable plastic bag With 100% aerobic decomposition in landfill (1500 bags)	Compostable plastic bag with 50% aerobic & 50% anaerobic decomposition in landfill (1500 bags)	Polyethylene Plastic Bag (1500 bags)
Production	0.03	0.15	0.15	0.03
Disposal	0.05	0.03	0.22	0.00
Total	0.08	0.18	0.37	0.04

Another increasingly important issue is the protection of water sources around the globe. Concerns have been raised over the long-term availability of water to support the expanding population's need for drinking, manufacturing, and agriculture. Table 38 shows the use of freshwater resources for each of the grocery bag systems studied. The standard polyethylene plastic bag uses significantly less water, compared with the paper or compostable grocery bag systems. Paper grocery bags use approximately 1 gallon of water for every bag, compared with the plastic bag system, which uses only .008 gallons per bag or 1 gallon for every 116 bags. Compostable grocery bags do not appear to provide any improvement over paper bags, and use far more water than the standard polyethylene plastic bag. It appears, therefore, that in switching to a paper bag or compostable plastic bag system to combat a litter problem, consumers will have to accept another significant trade-off—the increase in use of valuable water resources.

Table 38. Gross Freshwater Resources (gallons)					
	Paper Bag (1000 bags)	Compostable Plastic Bag (1000 bags)	Compostable Plastic Bag (1500 bags)	Polyethylene Plastic Bag (1000 bags)	Polyethylene Plastic Bag (1500 bags)
Public Supply	1000	660	1000	8	13
Other	4	12	17	32	45

Other environmental factors that show similar trends are the emission of acid rain gases and water pollutants. In both cases, paper bag and compostable bag systems show larger amounts of pollutants emitted into the environment than those emitted by the plastic grocery bag system. Similarly, there are other environmental matters that are important to consider when making a decision on which systems to implement. Paper bag systems use a completely different resource base—wood fiber—than the plastic bag system. If the wood fiber does not come from sustainably managed forest systems or from agricultural wastes, it may cause a trade-off that is unacceptable to consumers. Forests are important ecosystems that support a wide variety of life, and disrupting these ecosystems in the name of reducing litter is an effect that deserves further contemplation.

The study results support the conclusion that any decision to ban traditional polyethylene plastic grocery bags in favor of bags made from alternative materials (compostable plastic or recycled paper) will be counterproductive and result in a significant increase in environmental impacts across a number of categories from global warming effects to the use of precious potable water resources.

Addressing the issue of increasing litter with bans on plastic grocery bags may be counterproductive as this study has not considered many other mitigating circumstances that may lead to even greater differentials between plastic grocery bags and those made from either paper or compostable plastics.

Increased recycling rates for plastic bags, better bagging techniques at retail, and secondary uses of plastic grocery bags such as waste disposal could all further reduce the environmental impacts of plastic grocery bags. In addition, getting consumers to change their behavior so that plastic bags are kept out of the litter stream would appear to be more productive in reducing the overall environmental impact of plastic bags including litter.

This study supports the conclusion that the standard polyethylene grocery bag has significantly lower environmental impacts than a 30% recycled content paper bag and a compostable plastic bag. An LCA report and its findings can be used to demonstrate that an environmental impact analysis needs to take into account the entire picture, and when dealing with a product that is likely to be replaced by another, the trade-offs in the environmental impact of the replaced alternative should also be given a critical analysis.

LITERATURE REFERENCES

[1] Private communication between PBA member and Weyerhauser, June 2007.

[2] *Municipal Solid Waste in the USA: 2005 Facts & Figures,* USEPA, Office of Solid Waste, EPA530-R-06-011, October 2006.

[3] Boustead, I. *Eco-profiles of the European plastics industry: Report 3 – polyethylene and polypropylene.* A report for the European Centre for Plastics in the Environment (PWMI), Brussels, May 1993. Revised 1999.

[4] Private communications with BASF, Edwards, K. and Bradlee, C., May-July 2007.

[5] Vink, E. T. H., Rabago, K. R., Glassner, D. A., Gruber, P. R, *Applications of life cycle assessment to NatureWorks ™ polylactide (PLA) production.* Polymer Degradation and Stability 80 (2003) Elsevier, The Netherlands.

[6] Stodolsky, F., and Mintz, M. .M, *Energy Life-Cycle Analysis of Newspaper,* Energy Systems Division Argonne National Laboratory, Argonne, IL , May 1993.

[7] Robinson, W. D., *The Solid Waste Handbook,* John Wiley & Sons, New York, 1986.

[8] Methane Emissions, Energy Information Administration/Emissions of Greenhouse Gases in the United States 2001.

[9] Rathje, W., *Excavating Landfills,* Presentation at GRCDA 13'th Annual Landfill Gas Symposium. Lincolnshire, IL, 1990.

[10] Barlaz, M. A. *Carbon storage during biodegradation of municipal solid waste components in laboratory scale landfills.* Global Biochem. Cycles, 12(2):373-380, 1998.

[11] *Evaluation of the Performance of Rigid Plastic Packaging Containers, Bags, and Food Service Packaging in Full-Scale Commercial Composting*, A report to the Integrated Waste Management Board, California Environmental Protection Agency, Sacramento, CA, March 2007

[12] Houghton, J. T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. & Maskell, K. (eds). *Climate Change 1995 – Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, 1996.

[13] Evaluation of the Performance of Rigid Plastic Packaging Containers, Bags, and Food Service Packaging in Full Scale Commercial Composting. California State University, Chico Research Foundation. 2007. Prepared for the California Integrated Waste Management Board under Contract IWM-C2061.

[14] EPA of Polyethylene and Unbleached Paper Grocery Sacks, Prepared for the Solid Waste Council, Franklin Associates Report, June 1990.

[15] *Life Cycle Inventory of Packaging Options For Shipment of Retail Mail-order Soft Goods, Prepared For Oregon Dept. of Environmental Quality (DEQ) and* U.S. EPA Environmentally Preferable Purchasing Program, Franklin Associates, 2004.

[16] Evaluation des impacts environnementaux des sacs de caisse Carrefour. Analyse du cycle de vie de sacs decaisse en plastique, papier, et materriau biodegradable. Rapport prepare pour Carrefour. Fevrier 2004.

REFERENCES REGARDING THE BOUSTEAD MODEL

1. Boustead, I., *Boustead Model V5.0 Operating Manual*, Boustead Consulting Ltd., 2003.
2. Boustead, I., *Boustead Model V5.0 Code Book & Conversion Factors,*Boustead Consulting Ltd., 2003.
3. Boustead, I., *An Introduction to Life Cycle Assessment,*Boustead Consulting Ltd., 2003.
4. Boustead, I., *The Boustead Model Information Book, pages 1 – 500,* Boustead Consulting Ltd.

APPENDIX 1 – PEER REVIEW

Background

Dr. Overcash conducted the peer review and is a Professor of Chemical Engineering, as well as a Professor of Biological and Agricultural Engineering at North Carolina State University. Dr. Overcash has developed an in-depth national research program in life cycle research, developing the new areas for utilization of the life cycle tools. Dr. Overcash has led the effort in life cycle inventory techniques for manufacturing improvement and product change. Dr. Overcash has contributed to life cycle studies in energy production, electroplating, solvent selection, pharmaceutical processes, life cycle assessment comparisons, paper industry, and textiles. He has been active in European life cycle efforts and reviews of research in this field.

All of the suggestions and recommendations made by Dr. Overcash have been reviewed and incorporated in this report. Below is the Peer Review Report provided by Dr. Overcash.

Review of Draft Report
Life cycle assessment for three types of grocery bags – recyclable plastic; compostable, biodegradable plastic; and recycled, recyclable paper

By Dr. Michael Overcash
September 2, 2007

This report provides both a sound technical descriptions of the grocery bag products and the processes of life cycle use. The functional unit has a range to accommodate differences in customer use found to exist. These differences did not prove to change the resulting low environmental impact choice. The discussion of the limitations of the life cycle impact assessment is very important and the readers should use these observations. The following detailed review is divided into technical and editorial segments.

The conclusions regarding the relative environmental impact when using a life cycle view are consistent with previous studies and need to be reinforced in the policy arena. The policies to discourage plastic bags may have more to do with litter than the overall environment. Whatever the goals of the policy makers, these need to be far more explicit than general environmental improvement, since the life cycle story is consistent in favor of recyclable plastic bags. It is possible that the emphasis of another report might be that the full benefit of plastic bags is even higher when large recycling is in place.

Technical

1) p.3 last paragraph BBL is not defined
2) Table 3 at 5.78 kg functional unit this mass reflects the 50% water in wood. However this wood is lignin and cellulose and so only about 50% of the solid material ends up in paper bag, so this should be 274,000,000 mg

3) Table 5 These occur in all the raw material Tables
    a. Biomass is double counted as it appears also in Table 3 while wood does not appear both places
    b. Limestone is listed twice, here and as chalk
    c. N2 and O2 are listed twice as air and constituents of air
4) Table 7 This is an unusually high COD:BOD ratio, it might need to be checked
5) Table 9B Elec = 103 This did not change from Table 9A, while all the other values did change reflecting the differences in number of bags.
6) p.34 line 4 under Solid Waste This identifies steam or electricity as possible energy recovery mechanisms, but Table 25 is only electricity. Steam would have a much higher recovery value
7) p.41 2nd line From the data in Table 28A this ratio is more like 3.5 and not 2.5
8) p. 42 3rd line From the data in Table 28B it is hard to see any ratio as high as 13

Editorial

1) p1 2nd line world for governments
2) p4 last para, 3rd line represent
3) whole document the conventional style is that data are plural, but throughout this documents that is mostly not followed. A search for the word data and inserting the correct verb will fix this.

Journal of Cleaner Production
Volume 201, 10 November 2018, Pages 1052-1060

Life cycle assessment of end-of-life treatments for plastic film waste

Ping Hou [a, b], Yifan Xu [a], Morteza Taiebat [a, c], Christian Lastoskie [c], Shelie A. Miller [a, c], Ming Xu [a, c]

https://doi.org/10.1016/j.jclepro.2018.07.278

Highlights

- Recycling films shows greater environmental benefit than landfill and incineration.
- Consumer drop-off has the highest environmental impacts among collection scenarios.
- Mass fraction of plastic film is the key parameter to improve environmental benefit.
- Recycling rate, utilization rate, and WTE conversion rate are important parameters.
- Cooperation from multi-stakeholder is required to increase recycling.

Abstract

different waste treatment scenarios for plastic films: landfill disposal of mixed waste; incineration of mixed waste; recycling of mixed waste; and recycling of recyclable waste. The results demonstrate a considerable advantage of recycling over landfill disposal or incineration. The main environmental benefit is from the recycle of plastics that can substitute for the production of plastics from virgin materials. From a sensitivity analysis, five key parameters are identified that affect the aggregate environmental impact including mass fraction of films in the waste, recycling rate, utilization rate, waste-to-energy conversion rate, and the type of energy can be substituted by the recovered energy from incineration.

Previous Next

Keywords

Plastic film waste; End-of-Life; Recycling; Incineration; Landfill; Life cycle assessment

1. Introduction

Film-based packaging, also known as flexible packaging, refers to any package or portion of a package for which the shape can be easily changed, including bags, pouches, labels, liners, wraps, rollstock, or other flexible products (Flexible Packaging Association, 2016). Flexible packaging utilizes the best qualities of materials such as plastic, paper, and aluminum foil to deliver a wide range of protective functions within the smallest possible amount of material (Flexible Packaging Association, 2016). Each flexible package is produced with particular film that has a unique combination of attributes for a specific application. For example, low-density polyethylene (LDPE) films have high clarity and moderate stretch ability, which can be used as bread bags. Conversely, high-density polyethylene (HDPE) films have certain degree of opacity and low stretch ability, which can be used as grocery bags and air cushions for packaging.

Owing to its adaptability and capability for conserving resources, the production of flexible packaging has been steadily growing over the past 10 years. In 2016, annual sales of flexible packaging in the U.S. were about $30.2 billion, comprising 19% of the $164 billion U.S. packaging industry and its second largest segment (Flexible Packaging Association, 2017).

identified as one of the major sources of methane emissions contributing to climate change (Kumar et al., 2004). Incineration reduces the need for landfill disposal and can recover energy from combustion of waste. However, hazardous air pollutants are generated and released during incineration (Wiles, 1996). Recycling meanwhile is generally recognized for its environmental benefit of allowing the reuse of discarded materials. Recycled plastic films can be used to make various new products, such as composite lumber, crates, and bags (The Association of Plastic Recyclers, 2018). Nonetheless, a survey of programs in 2010 shows that curbside sites for bag and film recycling are only accessible to 10.8% of the U.S. population (Moore Recycling Associates, 2012). Only few curbside collection programs accept plastic films because post-consumer films must be clean and dry to be recycled and films can clog sorting machines at materials recovery facilities (MRF) (The Association of Plastic Recyclers, 2018). Moreover, the collection and transportation of recyclable waste also consume energy and resources, the amounts of which vary and depend on the location and type of waste. Given these considerations, an analysis is presented herein of the environmental burdens and benefits of various end-of-life treatments for plastic film waste.

Life cycle assessment (LCA) is a method to assess the holistic environmental impacts of a product or process in all of its life cycle stages, including resource extraction, materials processing, manufacturing, transport, use, and end-of-life disposal. Because it encompasses all stages of a product's life cycle and a wide range of environmental impacts, LCA can help direct policy and technology development to avoid environmental burden shifting among different stages and types of impacts. Since the 1990s, researchers have conducted various LCA studies on waste management strategies (Mølgaard, 1995, Barton et al., 1996, Craighill and Powell, 1996). Björklund and Finnveden (2005) reviewed 40 LCA case studies and found that recycling is, in most cases, preferable to landfill disposal or incineration with respect to life cycle energy use and global warming potential. Laurent et al. (2014) reviewed 222 LCA studies of solid waste management systems and concluded that the LCA results largely depend upon local attributes.

The majority of the reviewed studies focused on solid waste management in Europe, with only a few addressing solid waste management in North America. Morris (2005) concluded that for most conventionally recoverable materials, recycling consumes less energy and imposes lower environmental burdens than landfill disposal or incineration. Cabaraban et al. (2008) determined that bioreactor landfill disposal is favored over in-vessel composting in terms of energy use, cost, and airborne and waterborne emissions. To balance environmental impacts and costs, Thorneloe et al. (2007) used a municipal solid waste decision support tool to assess options for waste management. Kaplan et al. (2009) applied an optimization model and showed tha consumer plastic films: recycling, landfill disposal, and incineration. Our results consider the tradeoffs between these options and identify processes within the waste management system that significantly contribute to environmental impacts. These insights are intended help guide the development of waste management strategies for post-consumer plastic films.

2. Material and methods

This study is conducted according to the standard four-step LCA procedure of ISO14040/14044 (ISO, 2006), as outlined in the following sections.

2.1. Goal and scope definition

The overall goal of the study is to compare the life cycle environmental impacts of several end-of-life treatments for post-consumer plastic films. Specific goals are to: (1) evaluate and compare environmental impacts of different end-of-life treatments under various collection and waste composition scenarios; (2) identify key parameters affecting the environmental impacts of film waste treatments; and (3) inform film waste management decisions.

The functional unit is chosen to be the film waste contained within one metric ton of either recyclable waste or mixed waste. Following Pressley et al. (2015), the mass fraction of plastic films is assumed to be 0.6% and 2% in recyclable waste and mixed waste, respectively.

The system boundary is defined as spanning from post-consumption to end-of-life (Fig. 1). After a packaged product has been used, its plastic film packaging, or any portion of the product that contains a plastic film, is discarded into either a mixed waste or a recyclable waste stream. Mixed waste is collected by trucks and sent to either a landfill site, an incinerator for energy recovery, or a materials recovery facility (MRF) for recycling. Recyclable waste is either collected by trucks or dropped off by consumers to specific collection sites, and then transported to a MRF for recycling. Residues generated during recycling are sent to landfill or to incinerators for energy recovery. In total, four scenarios are considered herein:

- Landfill disposal of plastic films in mixed waste;
- Incineration of plastic films in mixed waste;
- Recycling of plastic films in mixed waste; and
- Recycling of plastic films in recyclable waste.

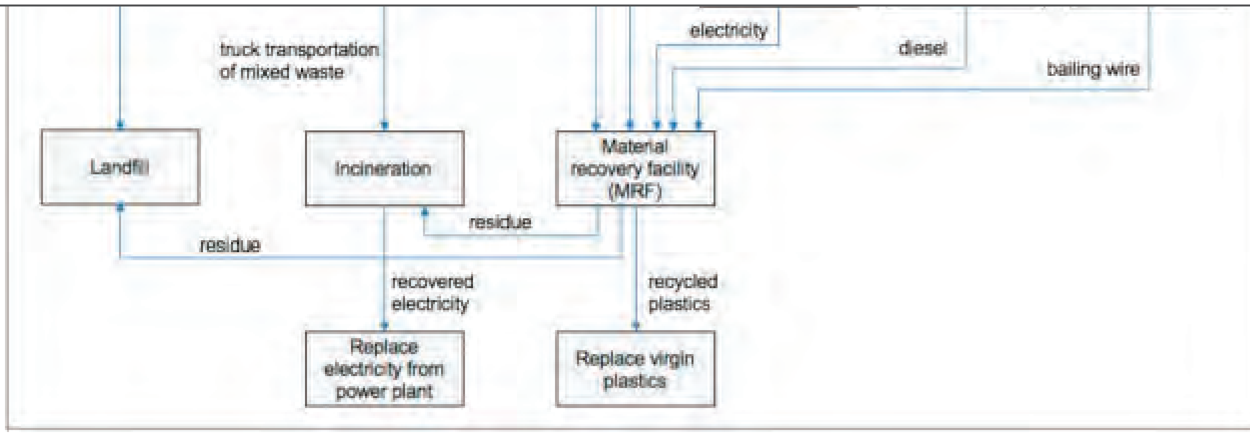


Fig. 1. Process flow diagram of the post-consumer plastic film treatment system.

Upstream processes prior to the post-consumption phase, including the manufacturing and distribution of plastic film products. However, these are not included in the present analysis, given that the purpose of this study is to compare different end-of-life treatments, for which the upstream processes may be considered equivalent. This study focuses on plastic film treatments in the U.S. and represents the industrial average.

2.2. Life cycle inventory analysis

Life cycle inventory (LCI) analysis quantifies the material and energy inputs and emission outputs of a product system. In our study, most of the data for foreground processes, including collection and treatment of waste via landfill, incineration, or recycling, are obtained from peer-reviewed, published studies. References are given when specific data are described. Background process data for upstream material use and transport are from the EcoInvent 2.2 database (EcoInvent, 2010). After all unit process data are compiled, process models and life cycle inventories are constructed for various film waste treatment scenarios using the SimaPro 8.4 LCA software environment (Pre Consultants, 2017).

2.2.1. Waste collection

rural areas requires approximately 5–6 times as much fuel as an urban route. Therefore, the collection distance for the rural scenario is obtained by multiplying the collection distance for the urban route by a factor of 6. Overall, the collection distance for recyclable waste on a unit mass basis is longer than for mixed waste because the amount of recyclable waste collected is smaller for a given route. For consumer drop-off, a default value of 10 miles (16.1 km) multiplying the fraction of dedicated trips (50%) is used for the roundtrip distance to drop-off site as obtained from the Municipal Solid Waste Decision Support Tool (MSW-DST) (Thorneloe et al., 1999) developed by the U.S. Environmental Protection Agency (EPA).

The above-mentioned collection distance indicates the distance per collection trip, which divided by the collected waste mass per trip derives the total distance for collecting per functional unit waste. Distance for transporting film waste is then calculated by multiplying the corresponding film mass fraction in recyclable or mixed waste (0.6% and 2%, respectively) (Table A.2). For mixed and recyclable waste collection by trucks, the EcoInvent 2.2 process for truck transport of municipal waste is used to characterize the environmental impact of waste collection (EcoInvent, 2010). For consumer drop-off, the corresponding process for passenger cars is used.

2.2.2. Recycling at MRF

Waste collected and sent to a MRF is sorted to separate and process its recyclable content. Electricity and diesel are consumed at MRF, and bailing wire is used for bundle recycled material. Table A.3 lists the energy and material consumption at a MRF for processing one metric ton of waste. Table A.4 shows the corresponding energy and material consumption with allocation to the film component of the waste stream based on their mass fraction in the waste. These data are for mechanical separation, the mainstream technology used for recycling at a MRF. Incidentally, if accepting film waste, equipment in MRF must be designed or modified to meet the special needs of recycling plastic films. For example, the blades must be properly sharped in order to sheer the films due to their soft, thin and malleable characteristics. Otherwise, films will wrap around the blades and clog the equipment (Testin and Vergano, 1997).

2.2.3. Replace virgin plastics

Recycled plastic films can be used to make composite lumber. They can also be processed into small pellets as raw material substitutes for making new plastic products. According to Pressley et al. (2015), the recycling rate of films is 90% for recyclable waste and 77% for mixed waste. The utilization rate of the recycled films is approximately 66% in the U.S. (Moore Recycling Associates Inc, 2016), which means 66% of the recycled films can be actually used to replace

The virgin plastics production processes in EcoInvent 2.2 (EcoInvent, 2010) are used to assess the environmental burdens avoided by virtue of plastic film recycling. Here, energy consumption associated with using recycled plastics for packaging applications is not considered, assuming it is the same as using virgin plastics.

2.2.4. Incineration

After film waste is processed at the MRF, the generated residue can be sent to incinerators for energy recovery. The residue rate is 76% for mixed waste and 10% for recyclable waste (Pressley et al., 2015). Collected mixed waste can also be directly sent to incinerators without recycling. Here, consideration is limited to energy recovery from the combustion of plastic films. It is assumed that the composition of the plastic films in the residue is the same as in the film waste. Table A.7 lists the plastic film composition in the residue sent for incineration and the heating value of each type of polymer. The amount of energy generated from combustion of these polymers is calculated assuming an electricity conversion efficiency of 7.7% (Wollny et al., 2001). From the electricity recovered, the mass fraction of the film waste, and the residue rate, the unit process data for incineration is obtained (Table A.8). The emission of hazardous substances such as dioxins generated by incineration are characterized using the incineration datasets in the EcoInvent 2.2 database (EcoInvent, 2010).

2.2.5. Landfill

As an alternative to incineration, residues generated at MRFs and collected mixed waste can be sent to landfill. The amount of film waste that goes to a landfill for burial corresponds to its mass fraction in the mixed waste. For MRF residues, the amount of waste designated for landfill disposal is calculated by multiplying the residual rate of the mixed or recyclable waste with the mass fraction of plastic films in the waste stream (Table A.9). Data characterizing the environmental impacts of landfills are acquired from the EcoInvent 2.2 database (EcoInvent, 2010).

2.3. Life cycle impact assessment

The Building for Environmental and Economic Sustainability method (BEES 4.0) (Lippiatt, 2007) is used to transform the life cycle inventory results into corresponding impact category measures. BEES was developed based on the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (Bare, 2011). TRACI includes the impact categories of global warming potential, acidification potential, eutrophication potential, fossil fuel de of each impact category compared with national averages per capita per year, allowing comparisons across the various impact categories.

In addition to measuring environmental impacts by different categories in TRACI, BEES further includes weight for each impact category to aggregate all categories of impacts into a single score. We use the most recent weighting scheme developed in 2006 by EPA.

2.4. Interpretation

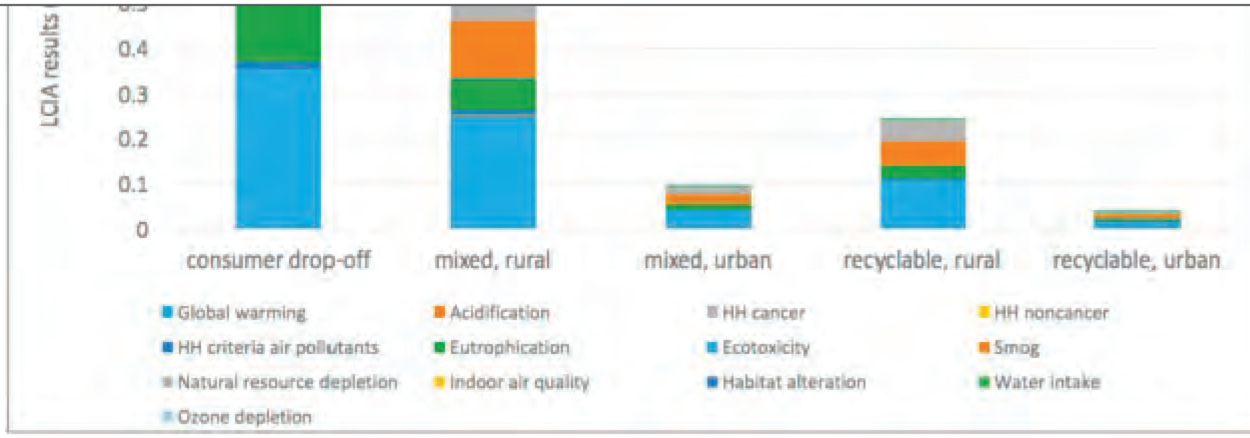
Since the scenarios investigated in this study do not comprehensively represent all prospective plastic film end-of-life treatments, analyses are conducted to identify and assess the sensitivity of the results to key parameters. Parameters so considered include the collection distance, electricity and diesel consumption at the MRF, recycling rate at the MRF, utilization rate of recycled films, waste-to-energy conversion ratio of the incinerator, type of energy can be substituted by the recovered energy, and mass fraction of films in the waste.

3. Results

Five waste collection scenarios and four MRF residue treatment scenarios are initially considered. The respective "worst-case" scenarios for mixed waste and for recyclable waste are then used as pessimistic conservative estimates to calculate the life cycle impacts of landfill disposal, incineration, and recycling of film waste.

3.1. Comparison of collection scenarios

Fig. 2 shows a comparison of the five collection scenarios. Among these scenarios, consumer drop-off has the highest environmental impact. This is because a passenger car hauls a much smaller amount of waste than a truck does; thus more passenger vehicle trips are needed to accumulate the same amount of waste that can be hauled by a truck. Waste collection in urban areas has a lesser environmental impact than in rural areas on account of the shorter collection distance. The principal environmental impacts attributed to collection are global warming, from carbon dioxide emissions during truck transportation; smog, from nitrogen oxides and particulate matters emissions; and natural resource depletion due to crude oil-based fuel consumption.



Download : Download high-res image (192KB) Download : Download full-size image

Fig. 2. Environmental impacts of different collection scenarios.

3.2. Comparison of MRF residue treatment scenarios

Fig. 3 shows a comparison of the four MRF residue treatment scenarios. Positive values indicate an environmental burden, whereas negative values denote an environmental benefit. Incineration has greater environmental burdens than landfill waste disposal across most of the impact categories. The principal impacts occur in the global warming category due to CO_2 emissions from incineration and the eutrophication category due to chemical oxygen demand in water. Environmental benefits principally accrue from energy recovery during incineration, which avoids the use of fossil fuels and to some extent therefore mitigates eutrophication, water resource appropriation, and natural resource depletion.

Download : Download high-res image (149KB) Download : Download full-size image

Fig. 3. Environmental impacts of different MRF residue treatment scenarios.

3.3. Comparison of waste treatment scenarios

Based on the results shown in Fig. 2, Fig. 3, a “worst-case” scenario is chosen that considers the disposition of waste gathered along a rural collection route, with incineration of the residues that are generated when waste is sent to a MRF for processing. Note the consumer drop off scenario is not considered because it is currently not a common practice and will not be encouraged based on our analysis. Fig. 4 compares the life cycle impacts of landfill disposal, incineration, and recycling (with incineration of MRF residues) of plastic films in mixed and recyclable waste streams. The results indicate that recycling of either mixed or recyclable waste confers a greater environmental benefit than either direct incineration or landfill disposal of mixed waste. Mixed waste recycling delivers a larger benefit than the recycle of “recyclable” waste, because the mass fraction of film waste is larger in mixed waste than in recyclable waste. The benefits of recycling are mainly manifested in the lower natural resource depletion, water intake, and eutrophication associated with the avoidance of virgin material production for plastic packaging.

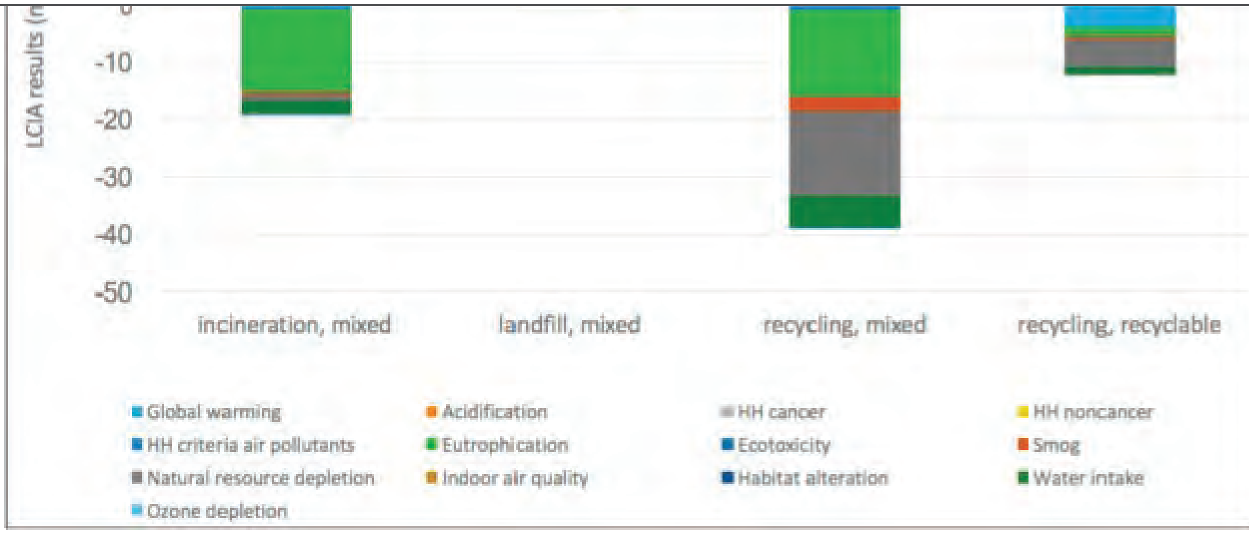
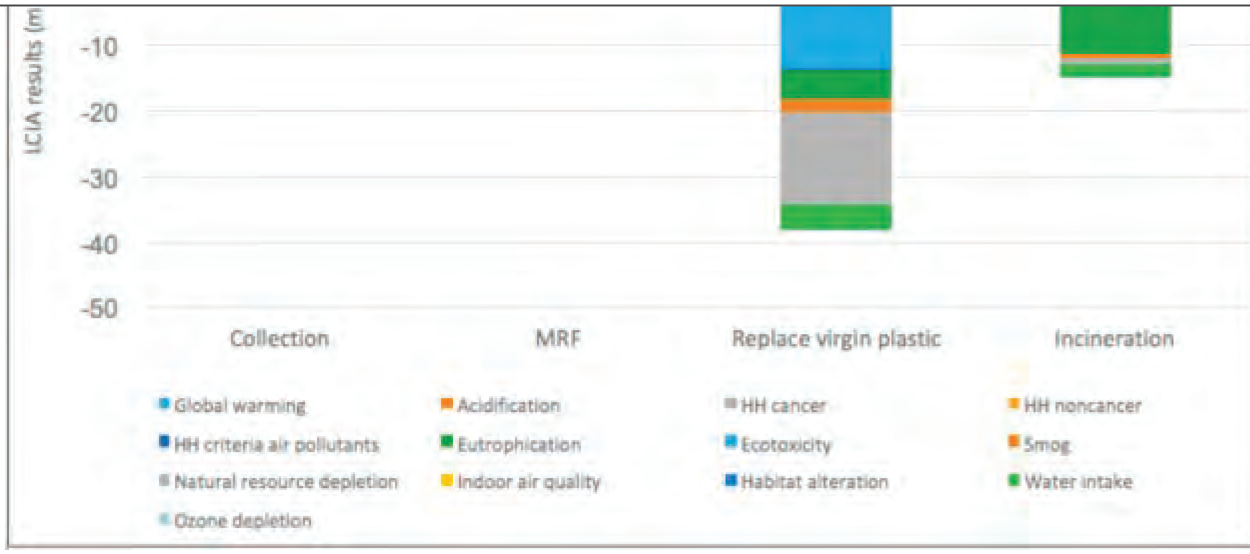


Fig. 4. Environmental impacts of different plastic film end-of-life treatment scenarios.

3.4. Comparison of different stages for recycling mixed waste

Fig. 5 shows the environmental impact results broken down by process step for the "best-case" scenario of Fig. 4 involving the recycle of plastic films from mixed waste. The incineration of the MRF residue is responsible for the largest environmental impacts, followed by environmental burdens associated with collection. The impact of MRF is almost negligible. The largest environmental benefit is from replacing virgin plastics, which reduces natural resource depletion and global warming.



Download : Download high-res image (176KB) Download : Download full-size image

Fig. 5. Environmental impacts of recycling plastic films from mixed waste by process step.

3.5. Sensitivity analysis

Table 1 shows the results of sensitivity analysis, wherein the sensitivity is calculated as:

$$\text{Sensitivity}=\left|\frac{\Delta output/output}{\Delta input/input}\right|$$

Table 1. Parameters in the sensitivity analysis.

Parameters	Description	Baseline	Extent of variation	Change in LCIA single-score result relative to baseline	Sensitivity
Collection	Total distance traveled by	1.08 km	75% longer	Increase 1.4%	0.02

distance	vehicles to collect or drop off 1 ton of waste		50% longer	Increase 0.9%	
			25% longer	Increase 0.5%	
			25% shorter	Decrease 0.5%	
			50% shorter	Decrease 0.9%	
			75% shorter	Decrease 1.4%	
Electricity and diesel fuel consumption at MRF	Electricity and diesel consumed at MRF to separate plastic film waste from other waste	0.156 kWh electricity and 0.546 MJ diesel	75% higher	Increase 0.9%	0.01
			50% higher	Increase 0.6%	
			25% higher	Increase 0.3%	
			25% lower	Decrease 0.3%	
			50% lower	Decrease 0.6%	
			75% lower	Decrease 0.9%	
Recycling rate at MRF	Percentage of plastic film waste that can be recycled	77%	50%	Increase 35%	1.22
			60%	Increase 22%	
			70%	Increase 9%	
			80%	Decrease 4%	
			90%	Decrease 17%	
Utilization rate of recycled plastic films	Percentage of recycled plastic films used to replace the virgin plastic	66%	50%	Increase 30%	1.22
			60%	Increase 11%	
			70%	Decrease 7%	
			80%	Decrease 26%	
			90%	Decrease 44%	
Waste-to-energy conversion rate at incinerators	Electricity that can be substituted by plastic film waste incineration	7.7%	10%	Decrease 24%	0.81
			20%	Decrease 129%	
			30%	Decrease 233%	

			40%	Decrease 338%	
			50%	Decrease 443%	
Type of electricity replaced at incinerators	Energy source replaced by electricity recovered from incinerating MRF recycling residues	US average mix	Coal	Decrease 47%	NA
			natural gas	Increase 48%	
			Solar photovoltaic	Increase 72%	
			nuclear	Increase 77%	
			hydro	Increase 80%	
Mass fraction of films in the waste	The weight percentage of films in the mixed waste	2%	5%	Decrease 299%	1.99
			10%	Decrease 797%	
			15%	Decrease 1296%	
			20%	Decrease 1794%	
			25%	Decrease 2292%	

The aggregate environmental impact is relatively insensitive to collection distance and to electricity and diesel consumption at the MRF. This is because, as observed in Fig. 5, the collection and MRF process stages are lesser contributors to the overall life cycle impact. In contrast, the model results are more sensitive to the mass fraction of films in the waste, utilization of combustion energy recovered at the incinerator, recycling rate at the MRF, and utilization rate of recycled plastic films. It bears noting that incinerator energy recovery only reduces the overall environmental impact (as measured through single-score results) if the recovered electricity displaces coal-fired power. Displacement of electricity generation from other energy sources, including natural gas, nuclear, solar photovoltaic, and hydropower, is not warranted according to the sensitivity analysis.

4. Discussion

hand, recycled plastic films substitute virgin materials and avoid the environmental impacts associated with the extraction and processing of these virgin materials. The cost-benefit analysis for the separate recycling of plastic films is a worthwhile subject that requires additional effort to investigate.

Second, the foreground unit process data in this study are all collected from peer-reviewed literature. Some of these data may not represent the industrial average of the U.S. For example, the data for collection distances in Table A.1 represent a city in the U.S., and the data for waste-to-energy conversion rates in Table A.7 reference incinerators operating in Germany. Sensitivity analysis is therefore performed to assess the effects of parametric variations. For consistency, background data are all obtained from the EcoInvent database, but when U.S.-based data are unavailable, European data are substituted, as in the case for the incineration and virgin plastic production processes.

Third, life cycle cost is not analyzed in this study. The evaluation of economic costs, as well as the potential social impacts of plastic film waste recycling, are required for a comprehensive sustainability assessment that will enable waste management planners and operators to make well-informed decisions (Ekvall et al., 2007).

5. Conclusions

The life cycle assessment conducted in this study indicates there is an environmental advantage for recycling plastic film waste rather than consigning it to landfill disposal or incineration. Recycling appears to be particularly favorable when the plastic film waste is recovered from mixed waste rather than from recyclable waste, on account of the higher mass fraction of plastic films in mixed waste, despite the lower recycle rate. This is not to suggest that recycling of plastic films from recyclable waste be discouraged. Rather, waste management. Instead, policies should encourage consumers to separate plastic films from mixed waste so as to increase the recoverable fraction of plastic films in recyclable waste. This is also confirmed by the sensitivity analyses that increasing the mass fraction of films in waste will significantly improve the environmental benefit of recycling.

Besides mass fraction of films in waste, sensitivity analysis also identified the recycling rate at the MRF, utilization rate, and incinerator waste-to-energy ratio as key parameters governing the life cycle environmental impacts of plastic film end-of-life treatments. More investigation is needed to collect data to better characterize MRF recycling, utilization, and waste incineration processes. Technology development should consider improvements to MRF recycling, utiliz offs are not encouraged. Effective policy design should consider how to make curbside collection sites available and convenient for more residents.

Since significant benefits are shown from recycling plastic films, additional resources should be dedicated to improving the overall recycling rate. There are still technical barriers for film recycling. Tailored equipment is needed for films recycling. However, to make the equipment investment economically variable, sufficient volume of plastic film waste is required. This requires the cooperation of multiple stakeholders. First, packaging designers should design clear and easy to understand labels indicating recyclability and provide necessary instructions, such as to keep the film dry and clean and to recycle it to specific collection sites. Second, communities should collaborate with industry experts to educate residents for plastic film recycling and encourage their participation. In addition, before the volume of recycled films is sufficient, public funding is required to make the recycling profitable.

Acknowledgement

This work was supported by Procter & Gamble through the MCubed Diamond Program at the University of Michigan.

Appendix.

Table A.1. Transportation data for collecting one metric ton of waste.

Parameters	**Mixed waste, urban**	**Mixed waste, rural**	**Recyclable waste, urban**	**Recyclable waste, rural**	**Consumer drop-off**	**Unit**	**Data source**
Distance between collection route and destination	20	120	35	208	NA	km	Data for mixed and recyclable waste are from Jaunich et al. (2016); Data for consumer drop-off are from MSW-DST

garage						
Distance between garage and collection route	6.0	36	3.5	21	NA	km
Total distance	54	324	78	470	16.1	km
Waste mass per trip	21[a]	21	21	21	0.015[b]	t

Note.

a

21 is the load of the transport dataset we use in EcoInvent, assuming the truck is fully loaded.

b

0.015 is calculated by 16.9 pounds (household recyclables generated per week) times 2 (recyclables dropped off every other week) times 0.00045t/pounds.

Table A.2. Unit process data for collecting one metric ton of film waste.

Materials	Mixed, urban	Mixed, rural	Recyclable, urban	Recyclable, rural	Consumer drop-off	Unit	Upstream processes
Truck transportation	0.05	0.31	0.02	0.13	NA	t km	Transport, municipal waste collection, lorry 21t/CH S
Consumer transportation	NA	NA	NA	NA	3.15	km	Transport, passenger car {RoW} | market for | Alloc Def, S

Note: The units of the two transportation system processes in EcoInvent are different, because the mass of the freight contributes a larger fraction of the total transported mass for truck transport of waste than for consumer drop-off of waste using passenger cars.

Electricity	7.8	6.2	kWh	Pressley et al., 2015
Diesel	0.7	0.7	L	
Bailing wire	0.6	0.3	kg	
Heat value of diesel	39	39	MJ/L	World Nuclear Association, 2016

Table A.4. Unit process data for MRF for disposal of one metric ton of film waste.

Materials	Mixed waste	Recyclable waste	Unit	Upstream processes
Electricity	0.16	0.37	kWh	Electricity, at grid, US/US
Diesel	0.55	0.16	MJ	Diesel, combusted in industrial equipment/US
Bailing wire	0.012	0.018	kg	Steel, unalloyed {GLO} market for Alloc Def, S

Table A.5. The composition of polymers in film waste.

Plastic film formats	bags	cut/wrap	flow warp	wraps	lay flat/pillow pouches	standup prouches	retort pouches	lidding	sleeve labels	shrink bunding	stretch films	r c b
Annual volume in 2012 (MM lbs)	4796	254	53	1365	3321	946	16	11	817	866	938	2
Composition of polymers in each plastic film format												
LDPE	61%	46%	–	72%	40%	32%	–	–	11%	1		

PET	–	–	–	–	29%	60%	18%	40%	21%	–	–	–
PP	–	38%	100%	–	30%	–	42%	10%	5%	–	–	–
PVC	–	–	–	–	–	–	–	–	54%	–	–	–
PS	–	–	–	–	–	–	–	–	9%	–	–	–
Calculated composition of polymers in film waste (MM lbs)												
LDPE	2926	117	0	983	1328	303	0	0	90.	866	938	4
HDPE	96	28	0	0	0	0	0	0	0	0	0	8
PET	0	0	0	0	963	568	3	4	172	0	0	0
PP	0	96	53	0	996	0	7	1	41	0	0	0
PVC	0	0	0	0	0	0	0	0	441	0	0	0
PS	0	0	0	0	0	0	0	0	74	0	0	0
Total												

Table A.6. Avoided virgin plastics per metric ton of processed waste.

Materials	Mixed waste	Recyclable waste	Unit	Upstream processes
LDPE	–7.0	–2.46	kg	Polyethylene, LDPE, granulate, at plant/RER S
HDPE	–0.70	–0.24	kg	Polyethylene, HDPE, granulate, at plant/RER S
PET	–1.23	–0.43	kg	Polyethylene terephthalate, granulate, amorphous, at plant/RER S
PP	–0.86	–0.30	kg	Polypropylene, granulate, at plant/RER S
PVC	–0.32	–0.11	kg	Polyvinylchloride, at regional storage/RER S
PS	–0.05	–0.02	kg	Polystyrene, general purpose, GPPS, at plant/RER S

Polymer	Portion of film waste (%)	Lower heating value (MJ/ton)	Energy generated (kJ)	Data source
LDPE	68.9	44.3	30500	(Themelis and Mussche, 2014)
HDPE	6.8	44.3	3030	
PET	12.1	23.9	2900	
PP	8.5	44.3	3750	
PVC	3.1	19.2	600	
PS	0.5	41.5	216	
Total	100	–	41000	

Table A.8. Unit process data of incineration for disposal of one metric ton of waste.

Materials	Directly incinerated after collection (mixed waste)	Incineration after recycling at MRF		Unit	Upstream processes
		mixed waste	recyclable waste		
PE (LDPE &HDPE)	15.1	11.5	0.45	kg	Disposal, polyethylene, 0.4% water, to municipal incineration/CH S
PET	2.4	1.8	0.07	kg	Disposal, polyethylene terephthalate, 0.2% water, to municipal incineration/CH S
PP	1.7	1.3	0.05	kg	Disposal, polypropylene, 15.9% water, to municipal incineration/CH S
PVC	0.62	0.48	0.02	kg	Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH S
PS	0.10	0.08	0.003	kg	Disposal, polystyrene, 0.2% water, to municipal incineration/

Energy recovered	−63.2	−48.0	−1.9	MJ	Electricity, production mix US/US S

Table A.9. Unit process data for landfilling one metric ton of waste.

Materials	Directly sent to landfill after collection (Mixed waste)	Landfill disposal of residues after recycling at MRF		Unit	Upstream processes
		Mixed waste	Recyclable waste		
Landfill waste	20	15.2	0.6	kg	Disposal, plastic plaster, 0% water, to inert material landfill/CH S

Recommended articles Citing articles (31)

References

Bare, 2011 J. Bare
TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0
Clean Technol. Environ. Policy, 13 (2011), pp. 687-696
CrossRef View Record in Scopus Google Scholar

Bare et al., 2006 J. Bare, T. Gloria, G. Norris
Development of the method and US normalization database for life cycle impact assessment and sustainability metrics
Environ. Sci. Technol., 40 (2006), pp. 5108-5115
CrossRef View Record in Scopus Google Scholar

Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies
Resour. Conserv. Recycl., 44 (2005), pp. 309-317
Article Download PDF View Record in Scopus Google Scholar

Cabaraban et al., 2008 M.T.I. Cabaraban, M.V. Khire, E.C. Alocilja
Aerobic in-vessel composting versus bioreactor landfilling using life cycle inventory models
Clean Technol. Environ. Policy, 10 (2008), pp. 39-52
CrossRef View Record in Scopus Google Scholar

Craighill and Powell, 1996 A.L. Craighill, J.C. Powell
Lifecycle assessment and economic evaluation of recycling: a case study
Resour. Conserv. Recycl., 17 (1996), pp. 75-96
Article Download PDF View Record in Scopus Google Scholar

EcoInvent, 2010 EcoInvent
Ecoinvent Centre
(2010)
[WWW Document]. EcoInvent v.2.2 database
Google Scholar

Ekvall et al., 2007 T. Ekvall, G. Assefa, A. Björklund, O. Eriksson, G. Finnveden
What life-cycle assessment does and does not do in assessments of waste management
Waste Manag., 27 (2007), pp. 989-996
https://doi.org/10.1016/j.wasman.2007.02.015
Article Download PDF View Record in Scopus Google Scholar

Flexible Packaging Association, 2017 Flexible Packaging Association
2017 State of the Flexible Packaging Industry Report
(2017)
Google Scholar

Flexible Packaging Association, 2016 Flexible Packaging Association
Advantages of Flexible Packaging
(2016)
Google Scholar

Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumber Containers and Packaging
(2011)
Google Scholar

ISO, 2006 ISO, E.N
14040: 2006. Environ. Manag. cycle assessment-Principles Fram
Eur. Comm. Stand (2006)
Google Scholar

Jaunich et al., 2016 M.K. Jaunich, J.W. Levis, J.F. DeCarolis, E.V. Gaston, M.A. Barlaz, S.L. Bartelt-Hunt, E.G. Jones, L. Hauser, R. Jaikumar
Characterization of municipal solid waste collection operations
Resour. Conserv. Recycl., 114 (2016), pp. 92-102
https://doi.org/10.1016/j.resconrec.2016.07.012
Article Download PDF View Record in Scopus Google Scholar

Kaplan et al., 2009 P.O. Kaplan, S.R. Ranjithan, M.A. Barlaz
Use of Life-cycle Analysis to Support Solid Waste Management Planning for Delaware
(2009)
Google Scholar

Kumar et al., 2004 S. Kumar, S.A. Gaikwad, A.V. Shekdar, P.S. Kshirsagar, R.N. Singh
Estimation method for national methane emission from solid waste landfills
Atmos. Environ., 38 (2004), pp. 3481-3487
Article Download PDF View Record in Scopus Google Scholar

Laurent et al., 2014 A. Laurent, I. Bakas, J. Clavreul, A. Bernstad, M. Niero, E. Gentil, M.Z. Hauschild, T.H. Christensen
Review of LCA studies of solid waste management systems–Part I: lessons learned and perspectives
Waste Manag., 34 (2014), pp. 573-588
Article Download PDF View Record in Scopus Google Scholar

Lippiatt, 2007 B.C. Lippiatt
BEES 4.0: Building for Environmental and Economic Sustainability. Technical Manual and User Guide

Article Download PDF View Record in Scopus Google Scholar

Moore, 2008 C.J. Moore
Synthetic polymers in the marine environment: a rapidly increasing, long-term threat
Environ. Res., 108 (2008), pp. 131-139
Article Download PDF View Record in Scopus Google Scholar

Moore Recycling Associates, 2012 Moore Recycling Associates
Plastic Film and Bag Recycling Collection: National Reach Study
(2012)
Google Scholar

Moore Recycling Associates Inc, 2016 Moore Recycling Associates Inc
2015 National Post-consumer Plastic Bag & Film Recycling Report
(2016)
Google Scholar

Morris, 2005 J. Morris
Comparative LCAs for curbside recycling versus either landfilling or incineration with energy recovery (12 pp)
Int. J. Life Cycle Assess., 10 (2005), pp. 273-284
CrossRef View Record in Scopus Google Scholar

Nguyen and Wilson, 2010 T.T.T. Nguyen, B.G. Wilson
Fuel consumption estimation for kerbside municipal solid waste (MSW) collection activities
Waste Manag. Res., 28 (2010), pp. 289-297
View Record in Scopus Google Scholar

Pre Consultants, 2017 Pre Consultants
SimaPro
(2017)
Google Scholar

Pressley et al., 2015 P.N. Pressley, J.W. Levis, A. Damgaard, M.A. Barlaz, J.F. DeCarolis
Analysis of material recovery facilities for use in life-cycle assessment
Waste Manag., 35 (2015), pp. 307-317

Environ. Int. (1997), pp. 1-28
View Record in Scopus Google Scholar

The Association of Plastic Recyclers, 2018 The Association of Plastic Recyclers
Plastic film recycling FAQs [WWW document]
Assoc. Plast. Recycl (2018)
Google Scholar

Themelis and Mussche, 2014 N.J. Themelis, C. Mussche
2014 energy and economic value of municipal solid waste (MSW)
Currently Landfilled in the Fifty States. Columbia Univ, vol. 40, Including Non-Recycled plastics (NRP) (2014)
Google Scholar

Thorneloe et al., 1999 S.A. Thorneloe, K. Weitz, M. Barlaz, R.K. Ham
Tools for determining sustainable waste management through application of life-cycle assessment: update on US Research
Seventh International Waste Management and Landfill Symposium V (1999), pp. 629-636
View Record in Scopus Google Scholar

Thorneloe et al., 2007 S.A. Thorneloe, K. Weitz, J. Jambeck
Application of the US decision support tool for materials and waste management
Waste Manag., 27 (2007), pp. 1006-1020
Article Download PDF View Record in Scopus Google Scholar

Wiles, 1996 C.C. Wiles
Municipal solid waste combustion ash: state-of-the-knowledge
J. Hazard Mater., 47 (1996), pp. 325-344
Article Download PDF View Record in Scopus Google Scholar

Wollny et al., 2001 V. Wollny, G. Dehoust, U.R. Fritsche, P. Weinem
Comparison of plastic packaging waste management options: feedstock recycling versus energy recovery in Germany
J. Ind. Ecol., 5 (2001), pp. 49-63
https://doi.org/10.1162/108819801760049468
View Record in Scopus Google Scholar

Cradle to Grave: The Life Cycle of Styrofoam®

By Andrea Kremer

Race, Poverty and the Urban Environment

Professor Raquel Pinderhughes

Urban Studies Program

San Francisco State University

Spring 2003

Introduction

- **This presentation focuses on polystyrene, more widely known as Styrofoam.**
- **This presentation is designed for educational purposes as it takes us through the cradle to grave lifecycle of Styrofoam, paying particular attention to the social, environmental and public health impacts of the processes associated with Styrofoam.**

Preview: Uses

- **We will look at the many different uses of Styrofoam. This will cover:**
  - **Food and beverage containers.**
  - **Packaging products.**
  - **Building insulation and materials.**
  - **Craft project material.**

Preview: Components

- In this section, we will look at the chemical components used to make Styrofoam.
  - Benzene
  - Styrene
  - Ethylene
  - Blowing Agents – CFCs and HCFCs

Preview: Workers' Health

- Here we will examine the health impacts on the workers of the Styrofoam manufacturing plants.
  - Benzene exposure.
  - Styrene exposure.
  - Ethylene exposure.

Preview: Consumer Health

- In this section we will look at possible health impacts we face from using Styrofoam beverage and food containers.
  - Chemical migration.
  - Styrene in fatty tissue and breast milk.

Preview: Distribution

- Here we will look at the concept of distribution.
  - Effects of transportation fuels and components on the environment and our health.

Preview: Waste

- In this section we will examine the different methods of dealing with used Styrofoam.
  - Reuse – pros and cons.
  - Recycle – pros and cons.
  - Incineration – pros and cons.
  - Land fill – cons.

Preview: Styrofoam Alternatives

- In this last section we will explore alternatives to using Styrofoam products.
  - Eco-foam.
  - Natural insulation.
  - Changing small habits for the better.

Styrofoam Uses: Food and Beverage Containers

Styrofoam, the Dow Chemical brand name for Polystyrene, is perhaps most widely known for its use as coffee cups, disposable plates and take-out containers.

The reasons for its popularity is that it has excellent insulating properties that keep hot products hot and cold products cold much longer than disposable paper cups and boxes.

Styrofoam Uses: Food and Beverage Containers

Here is a list of the different uses for polystyrene products related to our food.

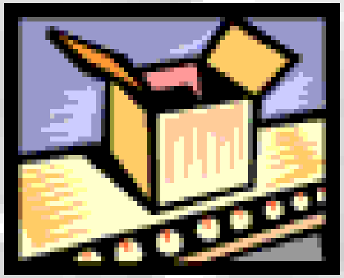
- Cups.
- Plates.
- Utensils (un-blown polystyrene).
- Take-out boxes.
- Egg cartons.
- Clear plastic cups and boxes (un-blown polystyrene).

Styrofoam Uses: Packaging Products

Using pre-molded Styrofoam or “peanuts” for packing delicate objects is probably the other most commonly known of use for this material.

For a long time, Styrofoam was the best packing material being light-weight and protective at the same time. However, in the past decade large, inflated air sacs have gained popularity as an even cheaper and effective packing material because it uses air and very few resources to create.

Styrofoam Uses: Packaging Products



- Most Styrofoam packaging is either the little popcorn-like pieces referred to as “peanuts” or the large molded piece to fit a specific product.
- If you ever come across packaging that looks like cut-up odd pieces of Styrofoam, it is re-used molded pieces that have been shredded down.

Styrofoam Uses: Building Insulation

This type of Styrofoam use is probably the highest consumer of Styrofoam altogether.

I say "probably" because there are so many different kinds of Styrofoam insulation and applications that they are too numerous to list, plus it is difficult to find reference resources that list the annual amount used of any of the types of Styrofoam insulation.

Styrofoam Uses: Building Insulation and Materials

Just to name a few uses…

- Flexible Styrofoam pipe insulation.
- Sheeted wall insulation.
- Spray Styrofoam wall insulation.
- Ground Styrofoam flake attack insulation.
- Insulation in products such as refrigerators and freezers.
- Base sheeting for stucco treatments.
- Concrete molding frames.

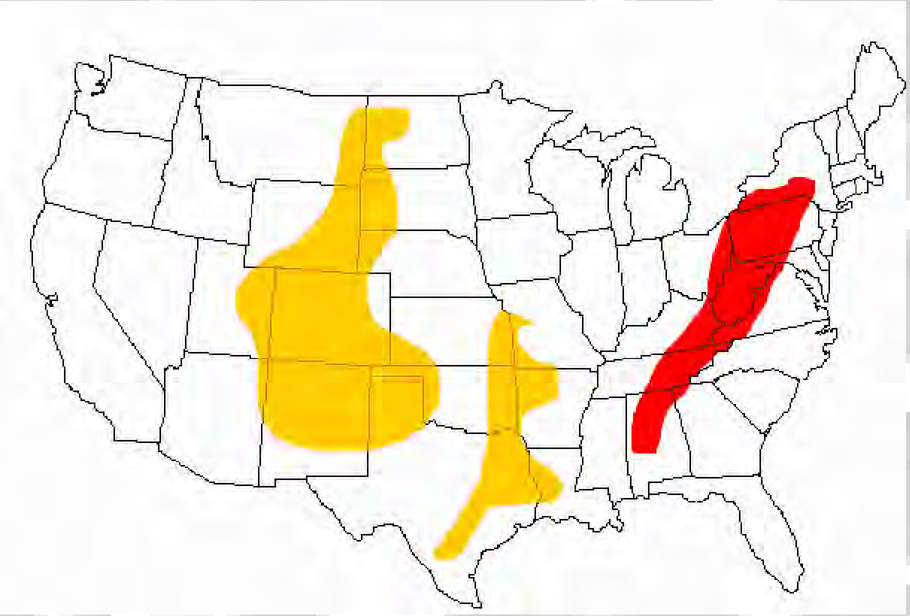
Styrofoam Uses: Craft Project Materials

- There is actually quite a large market for Styrofoam in the craft market.
- Some such uses are various sized donut-like Styrofoam pieces that people use as a base for all kinds of wreaths.
- There are many different shaped Styrofoam pieces for all sorts of projects, from arranging flowers to making architectural models. As with many craft materials, all you have to use is your imagination to figure out another use for this easily-molded substance.

Styrofoam Components: Benzene

Benzene is extracted from coal, but is also found in gasoline (2% present in U.S. gas and 5% present in gas from developing countries). Here is a map of the coal mines of the United States.

*The yellow areas are where scattered mines exist. The red area shows the greatest concentration of coal mines in the nation.



Styrofoam Components: Benzene

The extraction of coal is very hard on the natural environment. The earth distributed around the mine from deep inside is virtually dead in that it cannot support plant life. This leads to erosion of the land even long after the mine has been closed for use.

Working in the coal mines has always been known of as a very hazardous job.

Styrofoam Components: Benzene

- Benzene is a clear, colorless liquid with a noted pleasant odor.
- Benzene is present naturally in certain foods (I could not find out what foods it's present in).
- Another common name for Benzene is Coal Tar.
- Nearly 75% of all extracted Benzene is used in Polystyrene production. It is used to transform Styrene into Polystyrene (brittle plastic).
- Other common exposures to Benzene are from cigarette smoke (it is one of the 4,000 chemicals present) and from the exhaust pipes of automobiles.

Styrofoam Components: Styrene

- Styrene Monomer is a clear, oily liquid with a slight odor.
- Styrene for manufacturing is “cracked” or extracted from petroleum.
- I could not find the exact way Polystyrene is made, but it is basically a combination of Styrene and Benzene
- Styrene is naturally present in most foods, such as: strawberries, beef, coffee, peanuts, beans, wheat and cinnamon. The article that stated this also noted that the technology needed to detect Styrene present in natural food products is only two decades old. So, this could mean that Styrene has gotten into our natural environment through the refining of petroleum, but we haven’t been able to test for it until recently.

Styrofoam Components: Styrene

- **Styrene extraction is a $20 billion a year industry in the United States, comprising over 5,000 industrial plants in the following states: CA, IL, IN, LA, MI, NY, PA, OH & TX.**

Styrofoam Components: Ethylene

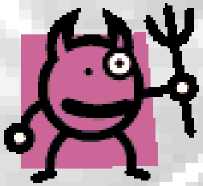
- Ethylene is a colorless gas that becomes a liquid at very low temperatures.
- Ethylene is present in almost every plant and encourages plant growth.
- Generally used as a refrigerant, it is one of the main building blocks of the petrochemical industry.
- Ethylene has been used as one of the two new blowing agents in the production of Styrofoam.

Styrofoam Components: Blowing Agents

- Polystyrene is basically a hard, brittle plastic (just like disposable plastic cups) and it doesn't become Styrofoam until it gets injected with a "blowing agent" to make it 30 times lighter than its original weight.
- The name, Polystyrene, doesn't change once it becomes Styrofoam, because the chemical composition doesn't change.
- To make Styrofoam, certain gases are injected into the plastic, blowing tiny holes that become gas and air filled pockets once the plastic cools. The background of this PowerPoint are the cells of Styrofoam.

Styrofoam Components: CFCs

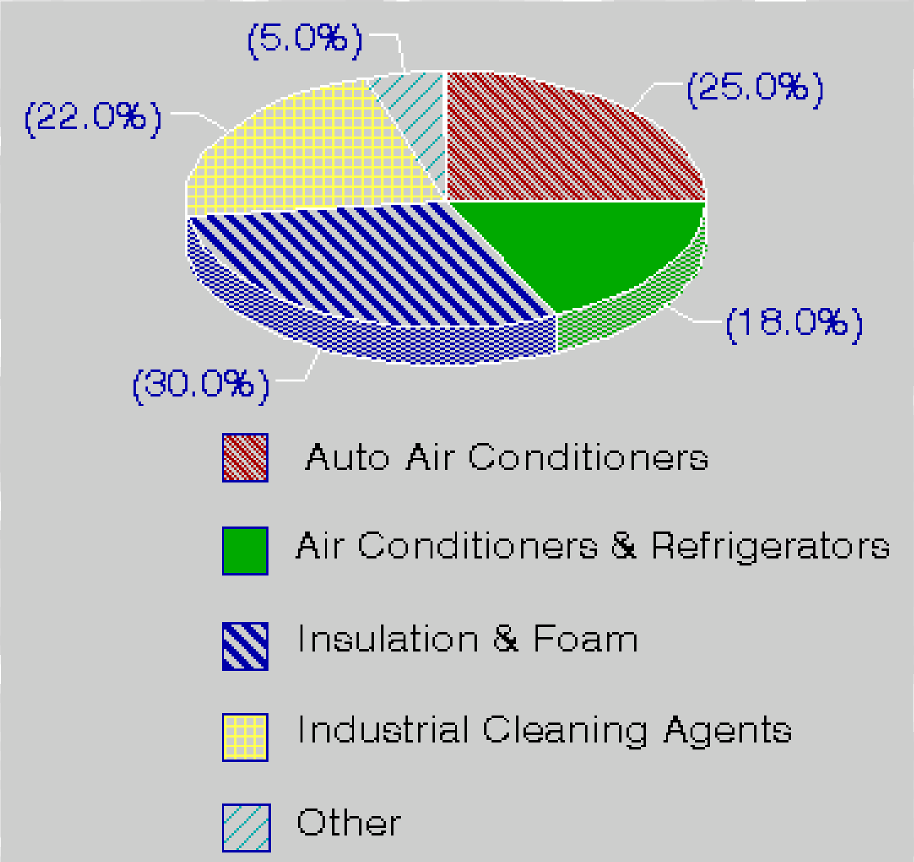
- Up until the late 1970’s CFCs, or Chlorofluorocarbons, were used as the blowing agents for Styrofoam production.
- The main CFC blowing agent was Isobutylene. This was phased out due to growing knowledge of the relationship between CFCs and global warming and replaced with HCFCs combined with Ethylene. Now before we move on to the controversy behind HCFCs, lets take a look at how the chemical companies and the EPA see the history of Styrofoam production differently.



Chemical Corporations' Take on CFCs

The largest pro-Polystyrene website (sponsored by Dow Chemical, Chevron Phillips and NOVA Chemical Corp, as well as six other chemical companies) stated that, "…most polystyrene foam products never were made with CFCs. Those few that did use CFCs comprised a very small portion of the U.S. CFC use."

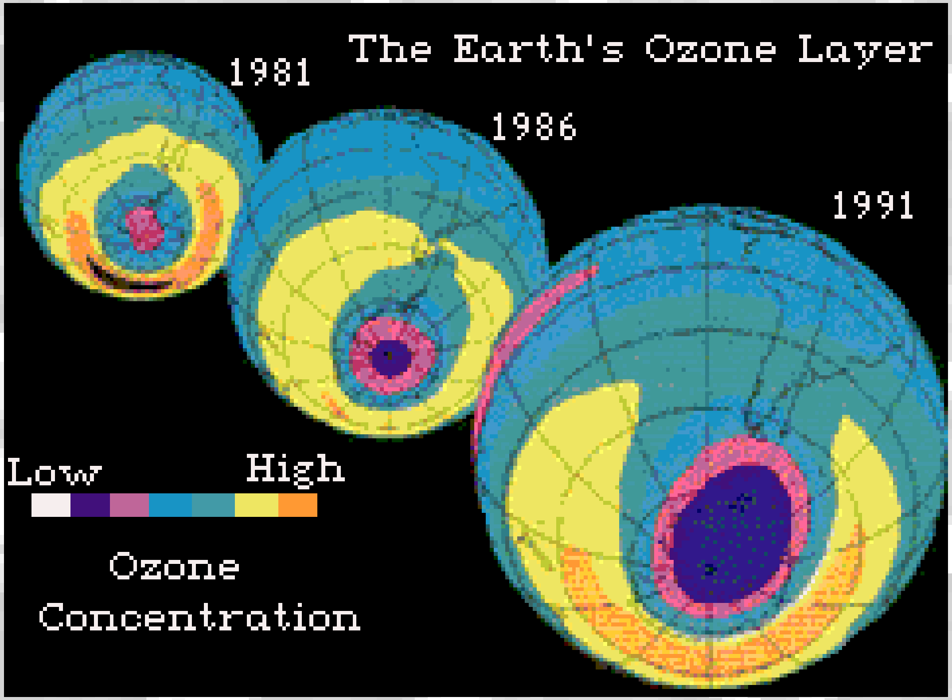
The EPA's Take on CFCs



The Environmental Protection Agency (EPA) had the opposite view of CFC use in Styrofoam production, and had a data chart to back up their statements. As you can see, insulation and foam make up 30% of the CFC use! I sure wouldn't consider that "a small portion of the U.S. CFC use."

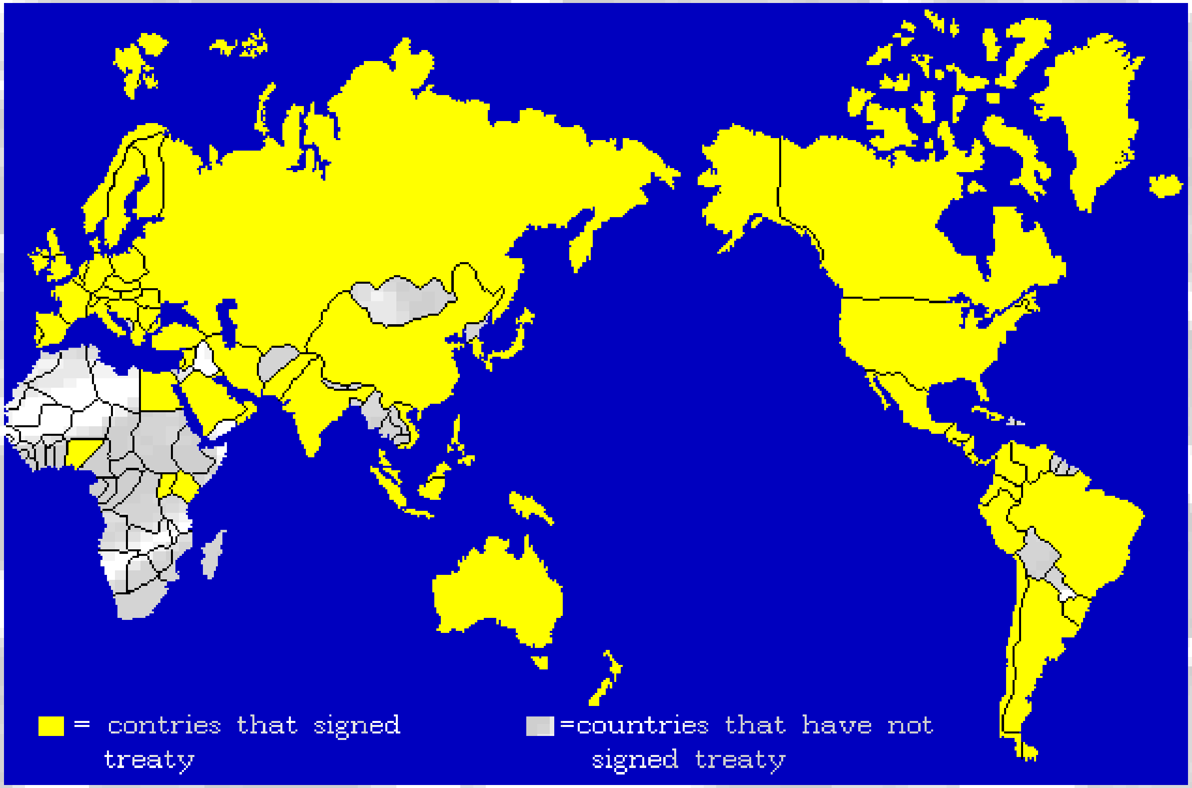
Global Warming

Another chart displayed on the EPA website is on the right. It shows how our Ozone Layer changed over only 10 years. The purple is an Ozone level of less than 2%. The Ozone Layer is the only protective barrier between us and harmful radiation from the Sun and outer space. This global threat is what lead to the Montreal Protocol.



Montreal Protocol

The Montreal Protocol on substances that Deplete the Ozone Layer was constructed in 1987 and signed by 35 countries to reduce the world's CFC production levels by 50% by 1998. This map shows the countries that signed (in yellow). However, in order to make this reduction of global warming truly effective, all countries needed to sign.



HCFCs

- **Hydrochloroflorocarbons are thought to be *less* harmful than regular old fashioned CFCs. In fact, HCFCs are supposed to be 90% less harmful than CFCs.**
- **For Styrofoam production, generally HCFC-22 is combined with Ethylene to create Ethylene Oxide (22% Ethylene).**
- **The fact that HCFC-22 is basically CFC-22 with a Hydrogen molecule attached (and CFC-22 was banned here in the late 1980’s) many people are skeptical of the idea that HCFCs are much better for the environment.**

Workers' Health: Benzene Exposure

- **Benzene is the most toxic of all the chemical components of Styrofoam and enters the human body either through the skin or respiratory system**
- **Benzene is listed on the Hazardous Substances List because it is a known MUTAGEN, CARCINOGEN and is FLAMABLE. Many scientist believe there are no safe exposure levels for carcinogens (cancer-causing agents). However, the Occupational Health and Safety Administration (OSHA) defines safe worker limits at 1 ppm (parts per million) over 8 hours and exposure of 5 ppm to not exceed 10 minutes.**

Workers' Health: Benzene Exposure

- Effects of short-term levels of exposure have been known to cause: dizziness, lightheadedness, headaches, vomiting, convulsions, coma, and death from irregular heartbeat.
- Effects of long-term levels of exposure have been known to cause: skin scaling, leukemia, plastic anemia, and death.

Workers' Health: Styrene Exposure

- Styrene is also very toxic in high levels, and is in the fatty tissue of every single one of us right now.
- Styrene is listed on the Hazardous Substances List as a MUTAGEN, FLAMABLE and REACTIVE. A mutagen alters one's chromosomal make-up. Styrene is also considered a neurotoxin.
- OSHA defines safe levels as 50 ppm over 8 hours and 100 ppm to not exceed 15 minutes.

Workers' Health: Styrene Exposure

- Exposure to Styrene at low levels for a short time can cause: eye, nose and throat irritation.
- Exposure to Styrene at higher levels for a short time can cause: dizziness, lightheadedness, loss of consciousness, trouble concentrating, memory problems, poor learning ability, brain damage, and death.
- Exposure to Styrene over months and years can cause: trouble balancing, learning impairments, fetal damage, decreased fertility in females, lung cancer, and shortened lifespan.

Workers' Health: Styrene Exposure Case Studies

- In several studies of human fat cells, 100% of the samples contained anywhere from 8 to 350 ng/g (nanograms per gram) of Styrene. 350 ng/g of Styrene is 1/3 the amount needed to cause neurological problems.
- In 12 breast milk samples, 75% were contaminated with Styrene.
- In Russia, Female workers exposed to vapors reported various menstruation problems, including excessive bleeding.
- In 1986, a worker exposed to Styrene vapors for five years complained of a burning sensation in his feet. Doctors found he had near total demyelination of the nerves in his feet (myelin is the protective sheathing allowing nerve signals to travel properly). The authors stated, "…Styrene affects the nervous system to a greater degree than formerly thought."

Workers’ Health: Ethylene Exposure

- Ethylene has not been found to be toxic.
- Ethylene is, however, on the Hazardous Substances List because in large quantities it can be FLAMABLE.
- High levels exposure can cause frostbite with direct contact and, like with many gases, can cause unconsciousness.
- As long as workers are properly trained and work at a properly regulated plant there should be little risk of explosion.

Consumer Health: Chemical Migration

Benzene exposure from automobile exhaust, gasoline vapors and cigarette smoke are more worrisome for us as documented thus far than from Styrofoam itself.

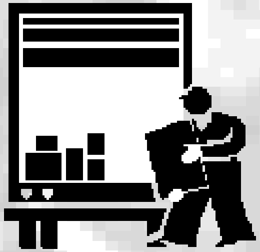
The dangers for non-workers are for those living in close proximity to the Styrofoam production plants and Petroleum refineries. The largest risks are with locally contaminated water from these plants (which is almost inevitable) and from vapors and soil contamination. I could not find any documents on any areas with contamination, nor contamination levels, but there was information stating the health risks of living near such an industrial plant.

It is very difficult to find any sort of actual harmful health effects from Styrofoam itself. There was evidence to suggest the *possible* migration of Styrene from Styrofoam food containers and cups into the food or drink it contains, but that many other resources suggesting nothing of the sort. So officially, the dangers of using Styrofoam in relation to food is inconclusive.

Consumer Health: Styrene Exposure

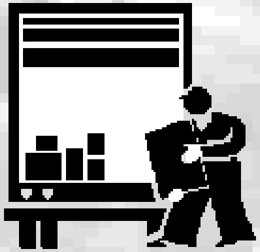
As mentioned earlier, Styrene is present in many foods, in our fatty tissue (documented 1972, 1976, 1982 & 1986), and present at high percentages in samples of breast milk. However, I found no documentation to *how* this chemical wound up inside us. The question still remains is this chemical *naturally* present in food, or has it originated there after years of petroleum-based pesticides and pollution? There needs to be similar studies done of those who live ecologically sound lifestyles far from developed areas might be a good indicator of whether this is a natural migration or an effect of petroleum-related product use.

Distribution: Fuel, Oil, and Break Pads



- Freight trucks run on diesel fuel that has over 40 toxic chemicals in its exhaust.
- Diesel fuel comes from crude oil and is extracted at petroleum plants. Diesel, like gasoline, contains Benzene.
- Break pad dust is now being linked to escalating asthma rates in children, and elevated cancer risks to those living near sections of freeways that experience high levels of traffic congestion.

Distribution: Fuel, Oil, and Break Pads



Now, a study of the pollution rates from freight trucks in relation to Styrofoam distribution is an entire study in itself. For this analysis, we need to realize that out of our 50 states, there are only a handful that have plants that manufacture Styrofoam. So approximately 80% of our nation gets its Styrofoam from over 500 miles away. That leaves us with a large amount of exhaust pollution, oil-to-groundwater seepage pollution, and break pad dust that escapes into our environment. All that so we can drink out of a Styrofoam cup for 20 minutes?

Styrofoam Waste Facts

- Here are the basic facts of Styrofoam waste:
  - Although Styrofoam breaks into pieces easily, it will take 500 years for one cup to dissolve. My unanswered question is: dissolve into what?
  - Our nation averages 547,945 tons of garbage per day and Styrofoam products make up 0.25% of this weight. It sounds a little more impressive when that comes out to 1,369 tons. Don’t forget, this stuff is pretty light weight. So, by volume Styrofoam waste takes up 25-30% of our nation’s land fill space.
  - There are over 25 million Styrofoam cups thrown away each year.

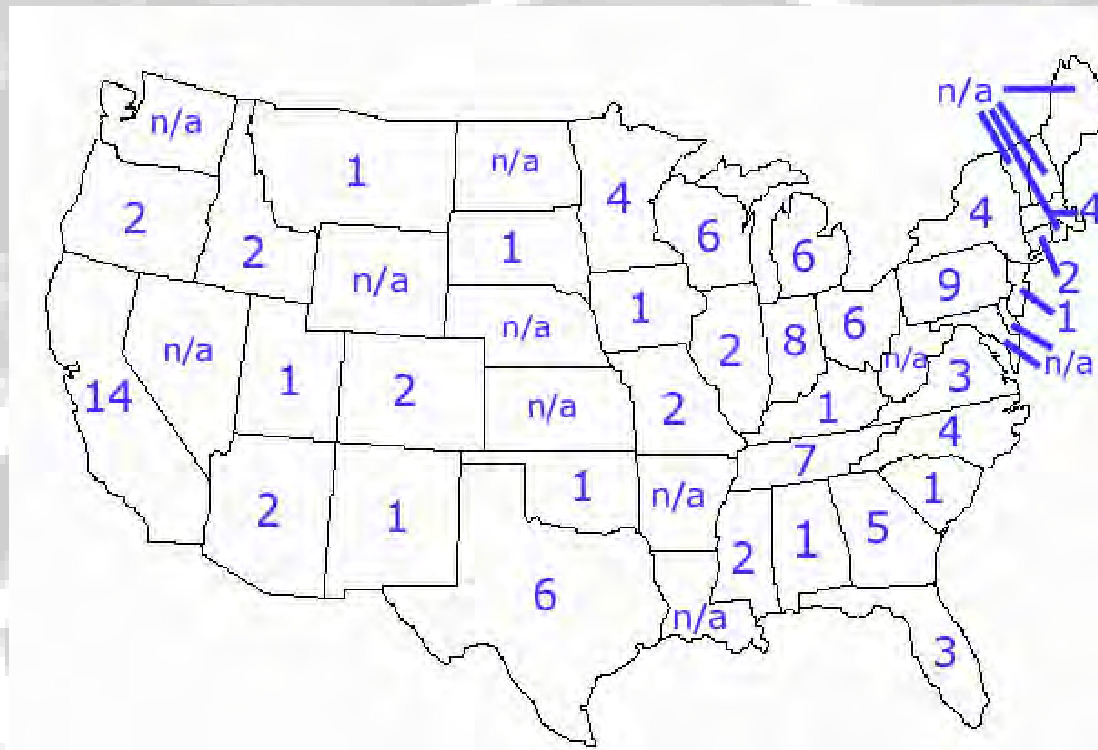
Styrofoam Reuse

- Foam insulation can be ground up and made into bean-bag chairs.
- Styrofoam sheeting insulation and molded Styrofoam can also be shredded to be used for packaging fillers.
- It would not be worthwhile to try and re-use a Styrofoam food or beverage container for its purpose for more than 2-3 times, because the material is flimsy and begins to break up. Cups can be re-used for plant seedlings, but then again there is the underlying issue of whether or not Styrene transfers to the plant itself.

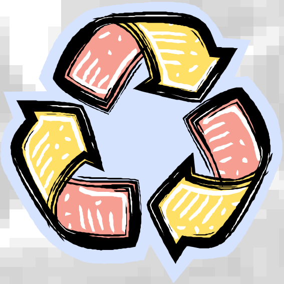
Styrofoam Recycling

- Recycling centers are limited in number.

Here's a map of all the recycling centers I could find in the United States (number of centers in each state).

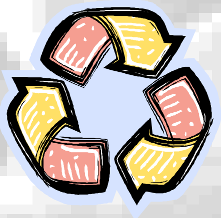


Styrofoam Recycling



When Styrofoam is recycled it's generally made into some other product that also has a low level of recycling patrons. Styrofoam is recycled into products like: cafeteria trays, video and audio tape bodies and cases, rules, desk top accessories, hangers, and horticultural plant trays. When was the last time you heard of many people actually recycling these products when their use is up? I would imagine not very often.

Styrofoam Recycling



- Out of the other alternatives we will look at for dealing with *waste*, recycling is the best option.
- What we need are more strict government regulations toward pro-Styrofoam recycling, such as curb-side pick up along with other recyclables.

Styrofoam Incineration

- Burning Styrofoam gives of over 90 different hazardous chemicals, including Styrene vapors and dioxins.
- If incinerated in extremely specialized plants, these vapors can be controlled, more often then not incineration facilities do not have the huge amount of financial resources to keep their plant operating at these extremely controlled levels. Thus, people living near these plants face a greater risk of developing health problems. And, normally these risk falls upon the poor who cannot afford to move as far from the incineration plants as the wealthy and middle class.

Styrofoam in Landfills

- Can make up to 30% of the garbage volume in landfills.
- Takes half a millennia to dissolve.
- Because of the landfill strategy of compacting the garbage and then packing dirt on top, practically nothing breaks down as it should, and that methodology winds up giving paper the same decomposition time as Styrofoam.
- Styrofoam captures water from seeping into the soil and therefore allows water to soak garbage until it's almost a soup-like mixture. When heavy rains come, this soup escapes the Styrofoam barrier onto the landfill lining (if there is one) or more likely off into our soil and groundwater.

Styrofoam Alternatives: Eco-Foam®

- Made from corn (starch).
- Creates no static-electricity (as does Styrofoam) and is much better for protecting very delicate electronics, like microchips.
- You can put it in your backyard compost, i.e . it's 100% biodegradable (as long as it's not packed down in a landfill).
- Comes in nearly everything from packaging "peanuts" to molded Eco-foam and insulation, plates, cups, and utensils (they make biodegradable trash bags, too).

Styrofoam Alternatives: Natural Insulation

- M.I.T. developed straw insulation that costs half as much as Styrofoam insulation, is non-toxic and is biodegradable.
- Made with an easily renewable, natural resource.

- Straw plus a sticky adhesive agent and compression = eco-friendly insulation.
- Predicted to be great for building in developing countries because of low cost and very easy to manufacture.

Styrofoam Alternatives: Changing Habits

- Use reuseable cups such as ceramic mugs, plastic cups, or plastic-lined stainless steal containers.
- If you *must* have disposable dinnerware, try the Eco-foam plates, cups and utensils.
- Buy your eggs in recycled paper cartons instead of Styrofoam.
- Buy meat that is packaged in plastic bags (like a whole chicken) instead of Styrofoam containers (its cheaper, too).
- Sit down to eat at a restaurant instead of ordering take-out (chances are it will be a healthier meal than take-out also).

References

- Plastic Loosefill Council (for a recycler near you). 1(800)828-2214.
- www.eco-foam.com
- www.ucdavis.edu
- www.afcee.af.mil
- www.mit.edu
- www.eco-usa.net
- www.enet.org
- www.deq.state.la.us
- www.styrene.org
- www.polystyrene.org
- www.epa.org
- www.kes-pro.com

References (Continued)

- www.styreneforum.org
- www.satyamplastics.com
- www.miramar.sdccd.cc.ca.us
- www.sci.newsfactor.com
- www.illinoisbiz.coal.pdf
- www.winow.org
- www.atsdr.cdc.gov
- www.spub.ksu.edu
- www.ccme.ca
- www.healthyvermonters.info
- www.ilsr.org
- www.newton.dep.anl.gov
- www.californialung.org
- Pinderhughes, Raquel. Spring 2003 Course Reader: Volume I & II

Thank You

Bottle Bill Resource Guide

(https://twitter.com/CRI_Recycle)
(https://www.facebook.com/container.recycling/)
(https://www.linkedin.com/company/container-recycling-institute)

National Bottle Bill

There is currently no nation-wide bottle bill implemented in the United States as of March 2021. However, there have been multiple efforts to pass such legislation, and there are two pieces of legislation up for consideration in the US Congress that would implement a national beverage container program: ***The Break Free from Plastic Pollution Act****, and* ***The CLEAN Future Act.***

The Break Free from Plastic Pollution Act

Name	S.984 - A bill to amend the Solid Waste Disposal Act to reduce the production and use of certain single-use plastic products and packaging, to improve the responsibility of producers in the design, collection, reuse, recycling, and disposal of their consumer products and packaging, to prevent pollution from consumer products and packaging from entering into animal and human food chains and waterways, and for other purposes. Also known as: The Break Free from Plastic Pollution Act of 2021 (amended to The Solid Waste Disposal Act, or 42 7 U.S.C. 6901 et seq.)
Date Introduced	25 March 2021
Beverages Covered	• Sparkling and non-sparkling water (including mineral water) • Carbonated soft drinks • Tea and coffee • Fruit juices (including coconut water) • Yogurt and probiotic drinks • Energy drinks • Sports drinks • Wines, wine coolers, and hard ciders • Liquor • Beer and malt beverages

Containers Covered	Containers ≤3L made of the following materials: • Glass • Plastic • Metal
Beverages Not Covered	• Infant formula • Meal replacements • Liquid drugs (as regulated by the Federal Food, Drug, and Cosmetic Act)
Containers Not Covered	• Cartons • Pouches • Aseptic containers
Amount of Deposit	10¢ USD
Reclamation System	Return to retail or to redemption centers
Handling Fee	TBD
Other Fees	TBD
Unredeemed Deposits	Kept by producers/distributors
Complementary Recycling Programs	There are local and statewide recycling programs, including curbside recycling. Ten states and one territory already have an existing bottle deposit program available.

Details

In the United States, there is no national bottle deposit scheme; ten states, and Guam, have implemented their own bottle deposit program instead. In 2003, US Senator Jim Jeffords tried to introduce a national bottle bill with the National Beverage Producer Responsibility Act. This bill ultimately failed to pass. [1] In February 2020, US House Representative Alan Lowenthal (CA) introduced Break Free From Plastic Pollution Act of 2020 which laid out various guidelines for national waste management systems and regulations in the US, including the implementation of a national bottle container program. [2] This legislation ultimately did not get past the Subcommittee on Water Resources and Environment.

For the 117th Congress, Representative Lowenthal and Senator Jeff Merkley (OR) introduced a new version of this act, the Break Free From Plastic Pollution Act on 25 March 2021. The bill is an omnibus bill that encompasses many different topics for better waste management and plastic reduction nationwide, including implementing an Extended Producer Responsibility (EPR) policy program for packaging and printed paper; a national standardization of recycling and composting; an imposition of a plastic bag fee; actions relating to the reduction of plastic and microplastic pollution; instating minimum recycled content requirements for beverage containers; and the implementation of a national beverage container deposit program.

The proposed deposit program would implement a 10¢ USD deposit on all eligible containers, subject to inflation and other factors. Consumers would be able to return their eligible containers at retailers and licensed redemption centers. Currently, the bill does not reflect the deposit status of beverages made of dairy or dairy alternatives. Unclaimed refunds will be retained by beverage producers to "supplement investments in nationwide collection and recycling infrastructure." [3] States which have already passed a comprehensive bottle bill prior to its passing, or states which will pass similar bottle bill legislation, may comply through their legislation instead if their legislation covers the same beverage type requirements and minimum deposit amount of 10 cents as the national bill.

At its introduction, S.984 was endorsed by over 400 environmental advocacy groups and organizations which wrote in support of the Act, including the National Audobon Society, the Sierra Club, and the World Wildlife Fund (WWF). [4] Such a program would foster and move container waste and recycling towards a circular economy, raising both national and state-level recycling rates.

The CLEAN Future Act

Name	H.R.1512 - To build a clean and prosperous future by addressing the climate crisis, protecting the health and welfare of all Americans, and putting the Nation on the path to a net-zero greenhouse gas economy by 2050, and for other purposes. Also known as: Climate Leadership and Environmental Action for our Nation’s (CLEAN) Future Act
Date Introduced	2 March 2021

Beverages Covered	• Sparkling and non-sparkling water • Mineral and soda water (flavored and unflavored) • Carbonated soft drinks • Tea and coffee • Fruit juices (including coconut water) • Dairy and dairy alternatives • Yogurt and probiotic drinks • Energy drinks • Sports drinks • Kombucha • Wines, wine coolers, and hard ciders • Liquor • Beer and malt beverages • Beverages containing hemp or marijuana
Containers Covered	Containers ≤3L made of the following materials: • Glass • Plastic • Metal
Beverages Not Covered	• Infant formula • Meal and caloric replacements • Liquid drugs (as regulated by the Federal Food, Drug, and Cosmetic Act)
Containers Not Covered	• Cartons • Foil pouches • Drink boxes
Amount of Deposit	10¢ USD
Reclamation System	Return to retail or to redemption centers
Handling Fee	TBD
Other Fees	TBD
Unredeemed Deposits	Kept by system administrator

Details

On 2 March 2020, The Climate Leadership and Environmental Action for our Nation's (CLEAN) Future Act, was introduced by US House Representative Frank Pallone, Jr. (NJ), US House Representative Paul Tonko (NY), and US House Representative Bobby L. Rush (IL). It was formed in the Energy and Commerce Committee as a result of the last two years' worth of hearings regarding to climate crisis. [5]

The bill encompasses many different regulations and set goals for the US, including: national pollution goals and emissions standards; increased dam safety measures; federal electricity regulatory reform; infrastructure modernization and improvement; and improved waste management and collection. This bill would also amend the Solid Waste Disposal Act to implement a federal bottle bill program. It would also conduct studies to determine the efficacy and implementation of such a program. Under this bill, unredeemed deposits go back towards the designated system administrator.

Footnotes

[1] S.1867 - National Beverage Producer Responsibility Act of 2003. 108th Congress (2003-2004). (https://www.congress.gov/bill/108th-congress/senate-bill/1867/actions?r=30&s=1)

[2] H.R.5845 - Break Free From Plastic Pollution Act of 2020. 116th Congress (2019-2020). (https://www.congress.gov/bill/116th-congress/house-bill/5845)

[3] "Break Free From Plastic Pollution Act: Overview." Offices of U.S. Senator Jeff Merkley and U.S. Representative Alan Lowenthal. 2021. (https://www.merkley.senate.gov/imo/media/doc/Break%20Free%20I %20Press%20Packet.pdf)

[4] "Letter of Support for the Break Free from Plastic Pollution Act of 2021." [PDF] (/images/PDF/BFPPPA_2021_Sign-on_List.pdf)

[5] "E&C LEADERS INTRODUCE THE CLEAN FUTURE ACT, COMPREHENSIVE LEGISLATION TO COMBAT THE CLIMATE CRISIS." (https://energycommerce.house.gov/newsroom/press-releases/ec-leaders-introduce-the-clean-future-act-comprehensive-legislation-to) House oCommittee on Energy & Commerce. 2 March 2020.

Last Updated on 24 March 2021.

MORE INFO - NATIONAL BOTTLE BILL

S.984 Break Free From Plastic Pollution Act

- S.984 Official US Congress Legislative Page (https://www.congress.gov/bill/117th-congress/senate-bill/984/all-info)
- Break Free From Plastic Pollution Act - Full Bill Text (/images/PDF/RYA21300.pdf)
- "Reps. Lowenthal, Clark, Senator Merkley Lead Introduction of Congress' Most Comprehensive Plan to Protect Americans' Health from Growing Plastic Pollution Crisis" (https://lowenthal.house.gov/media/press-releases/congressman-lowenthal-senator-merkley-lead-introduction-congress-most)

introduction-congress-most)

H.R.1512 CLEAN Future Act

- H.R.1512 Official US Congress Legislative Page (https://www.congress.gov/bill/117th-congress/house-bill/1512/all-actions-without-amendments?q=%7B%22search%22%3A%5B%22clean+future%22%5D%7D&s=1&r=1)
- Clean Future Act - Full Bill Text (/images/PDF/CleanFutureActBillText2021.pdf)
- "E&C Leaders Introduce The Clean Future Act, Comprehensive Legislation To Combat The Climate Crisis" (https://energycommerce.house.gov/newsroom/press-releases/ec-leaders-introduce-the-clean-future-act-comprehensive-legislation-to)

MORE ABOUT BOTTLE BILLS

Publications

Check out our our archive of publications on bottle bills and deposit legislation.

Links

Find links to related articles concerning bottle bills and legislation

Proposed Legislation

See a list of current proposed laws by state.

CONTAINER RECYCLING INSTITUTE

The Bottle Bill Resource Guide is an ongoing project of the Container Recycling Institute, dedicated to providing comprehensive information about beverage container deposit laws across the US and around the world.

Go to CRI (http://www.container-recycling.org)

CONTACT DETAILS

PHONE
310-559-7451

OFFICE
4361 Keystone Ave. Culver City, CA 90232

EMAIL
info@container-recycling.org