# RECYCLING

This chapter describes the development of material-specific emission factors for recycling in EPA's Waste Reduction Model (WARM). A discussion of forest carbon storage, an important input in calculating the emission benefits of paper product recycling, is also included in this chapter.

## 1. A SUMMARY OF THE GHG IMPLICATIONS OF RECYCLING

EPA defines recycling as "the separation and collection of wastes, their subsequent transformation or remanufacture into usable or marketable products or materials, and the purchase of products made from recyclable materials" (EPA, 2012). WARM considers the recycling of post-consumer materials, which are defined as a "material or finished product that has served its intended use and has been diverted or recovered from waste destined for disposal, having completed its life as a consumer item" (EPA, 2014).

Recycling is a process that takes materials or products that are at end of life and transforms them into either (1) the same product or (2) a secondary product (see discussion of open- and closed-loop recycling). When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. Consequently, recycling provides GHG reduction benefits in two ways, depending upon the material recycled: (1) it offsets a portion of "upstream" GHGs emitted in raw material acquisition, manufacture and transport of virgin inputs and materials, and (2) it increases the amount of carbon stored in forests (when wood and paper products are recycled).

In calculating the first source of GHG reduction benefits, WARM assumes that recycling materials does not cause a change in the amount of materials that would otherwise have been manufactured. Since the amount of products manufactured stays the same, and the existing demand for recycled content is the same, an increase in recycling leads to a displacement of virgin-sourced materials.

For more information on the second source of GHG reduction benefits that are provided by forest carbon storage, see the Forest Carbon Storage chapter.

### 1.1 OPEN- AND CLOSED-LOOP RECYCLING

Recycling processes can be broadly classified into two different categories: open-loop and closed-loop recycling. Most of the materials in WARM are modeled in a closed-loop recycling process, where end-of-life products are recycled into the same product. An example of a closed-loop recycling process is recycling an aluminum can back into another aluminum can. Decisions about whether to model materials in an open-loop or closed-loop process are based on how the material is most often recycled and the availability of data.

For materials recycled in an open loop, the products of the recycling process (secondary product) are not the same as the inputs (primary product). In open-loop emission factors, the GHG benefits of material recycling result from the avoided emissions associated with the virgin manufacture of the *secondary* products that the material is recycled into. Open-loop recycling does not account for avoided emissions from manufacturing the primary material, since recycling the recycled material does not displace manufacturing of the primary material. It only displaces manufacturing of the secondary product. For example, personal computers (PCs) are recycled by dismantling the PC and recovering and processing the raw materials it contains for use in secondary products. WARM models the plastics from PCs as being recycled into asphalt, rather than into new computer casings; the other materials in PCs also are recycled into non-PC products. Consequently, WARM calculates the GHG benefit from recycling PCs based on the emissions displaced from extracting and producing these secondary products from virgin inputs, rather than on the emissions displaced from manufacturing an entire new PC. In applying this method, EPA considers only the GHG benefit for one generation of recycling (i.e., future benefits from recycling the secondary products into additional products were not included).

The materials modeled as open-loop recycling processes in WARM are: mixed paper, corrugated containers (partial open-loop),[1] copper wire, carpet, personal computers, concrete, tires, fly ash, asphalt shingles and drywall (partial open-loop).[2] Corrugated containers and drywall are modeled as partial open-loop because the recycling emission factors for these materials are a weighted average of a closed-loop recycling pathway and an open-loop recycling pathway (e.g., 70 percent of recycled corrugated containers are used in production of more corrugated containers, and 30 percent of corrugated containers are recycled into boxboard). Fly ash is a special case: because it is a byproduct rather than a primary product, it would be impossible to recycle into additional primary product. For more detail on any of the materials mentioned, please refer to the material-specific chapter.

## 1.2 MATERIAL LOSSES

When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage (i.e., at collection and at the materials recovery facility) or in the manufacturing stage. Consequently, more than one short ton of material must be recovered and processed to produce one short ton of new material from the recycling process. Material losses are quantified and translated into loss rates. In this analysis, EPA used estimates of loss rates provided by Franklin Associates, Limited (FAL, 2003), for steel, dimensional lumber and medium-density fiberboard (the same materials for which FAL's energy data were used, as described in the Source Reduction chapter). Loss rates for a number of other materials were based on data compiled by EPA's Office of Research and Development (ORD) and the Research Triangle Institute (RTI, 2004). Material-specific sources were consulted for the remaining materials. These values are shown in Exhibit 1.

**Exhibit 1: Loss Rates for Recovered Materials**

| (a) Material | (b) % of Recovered Materials Retained in the Recovery Stage | (c) Short Tons of Product Made per Short Ton of Recycled Inputs In the Manufacturing Stage | (d) Short Tons of Product Made per Short Ton Recovered Materials (d = b × c) | (e) Data Source[a] |
|---|---|---|---|---|
| Aluminum Cans | 100 | 0.93 | 0.93 | RTI, 2004 |
| Aluminum Ingot | 100 | 0.93 | 0.93 | Aluminum cans used as proxy |
| Steel Cans | 100 | 0.98 | 0.98 | FAL, 2003 |
| Copper Wire | 82 | 0.99 | 0.81 | FAL, 2003 |
| Glass | 90 | 0.98 | 0.88 | FAL, 2003; RTI, 2004 |
| HDPE | 92 | 0.93 | 0.86 | FAL, 2011 |

[1] Note that corrugated containers are modeled using a partial open-loop recycling process. Roughly 70 percent of the recycled corrugated containers are closed-loop (i.e., replaces virgin corrugated) and 30 percent is open-loop (i.e., replaces boxboard).

[2] Most recycled drywall is used for a variety of agricultural purposes, but can also be recycled back into new drywall. Approximately 20 percent of recycled drywall is closed-loop (i.e., replaces virgin drywall) and 80 percent is open-loop (i.e., used for agricultural purposes).

| (a) Material | (b) % of Recovered Materials Retained in the Recovery Stage | (c) Short Tons of Product Made per Short Ton of Recycled Inputs In the Manufacturing Stage | (d) Short Tons of Product Made per Short Ton Recovered Materials (d = b × c) | (e) Data Source[a] |
|---|---|---|---|---|
| PET | 95 | 0.94 | 0.89 | FAL, 2011 |
| Corrugated Containers | 100 | 0.93 | 0.93 | FAL, 2003; RTI, 2004 |
| Magazines/Third-Class Mail | 95 | 0.71 | 0.67 | FAL, 2003; RTI, 2004 |
| Newspaper | 95 | 0.94 | 0.90 | FAL, 2003; RTI, 2004 |
| Office Paper | 91 | 0.66 | 0.60 | FAL, 2003; RTI, 2004 |
| Phone Books | 95 | 0.71 | 0.68 | FAL, 2003; RTI, 2004 |
| Textbooks | 95 | 0.69 | 0.66 | FAL, 2003; RTI, 2004 |
| Dimensional Lumber | 88 | 0.91 | 0.80 | FAL, 2003 |
| Medium-Density Fiberboard | 88 | 0.91 | 0.80 | FAL, 2003 |
| Personal Computers | 100 | 0.71[c] | 0.71 | FAL, 2002b |
| Concrete | 100 | 1.00 | 1.00 | See note d |
| Fly Ash | 100 | 1.00 | 1.00 | See note d |
| Tires | 90 | 0.86 | 0.78 | Corti & Lombardi, 2004 |
| Asphalt Concrete | 100 | 1.00 | 1.00 | Levis 2008[d] |
| Asphalt Shingles | 100 | 0.07 | 0.93 | Berenyi, 2007 |
| Drywall | 100 | 1.00 | 1.00 | WRAP, 2008 |

[a] Franklin Associates, Ltd. (FAL) provided data for column (b), while the Research Triangle Institute (RTI) provided data for column (c).
[b] A 0.5% loss rate was assumed for molded products from carpet recycling, based on data provided by FAL (2002a). No loss was assumed for the carpet pad/cushion and carpet backing. Since molded products make up 25% of the materials recovered from recycling carpet, the loss rate was weighted by this percentage to calculate the overall amount of material retained: (100% - 0.05% × 25%)/100 = 1.00.
[c] Weighted average of the materials that personal computers are assumed to be recycled into in an open-loop recycling process; i.e., asphalt, steel sheet, lead bullion, cathode ray tube (CRT) glass, copper wire and aluminum sheet.
[d] Due to the nature of the recycling process for fly ash and concrete, these materials are collected and recycled on a ton-per-ton basis, offsetting the production of portland cement and virgin aggregates, respectively.
[e] Loss rates for recycling asphalt concrete are less than 1% by mass. Since the recovered asphalt concrete is extremely valuable and typically recovered on-site, the retention rate for recovered asphalt concrete is quite high.
**Explanatory notes:** The value in column (b) accounts for losses such as recovered newspapers that were unsuitable for recycling because they were too wet. Column (c) reflects process waste losses at the manufacturing plant or mill. Column (d) is the product of the values in columns (b) and (c).

## 1.3 CALCULATING THE GHG IMPACTS OF RECYCLING

WARM assesses the GHG emission implications of recycling from the point of waste generation (i.e., starting at the point when the material is collected for recycling) through the point where the recycled material or product has been manufactured into a new product for use. This includes all of the GHG emissions associated with collecting, transporting, processing and recycling or manufacturing the recycled material into a new product for use. To account for the emissions associated with virgin manufacture, WARM calculates a “recycled input credit” by assuming that the recycled material avoids—or offsets—the upstream GHG emissions associated with producing the same amount of material from virgin inputs.

The approach for calculating the recycled input credit depends upon whether the material is recycled in a closed- or open-loop process. GHG emission reductions associated with closed-loop manufacture using recycled inputs are calculated by taking the difference between (1) the GHG emissions from manufacturing a material (accounting for loss rates) from 100-percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material from 100-percent virgin inputs.

For open-loop recycling processes, the emission reductions are calculated by taking the difference between (1) the GHG emissions from manufacturing a secondary product from 100-percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the secondary product (accounting for loss rates) from 100-percent virgin inputs.

The methodology for estimating resource acquisition and manufacturing emissions is described in the WARM Background and Overview chapter. There are separate estimates for manufacturing process emissions for virgin inputs and recycled inputs, and transportation for virgin inputs and recycled inputs. For details on the components of the manufacturing process and transportation inputs, see the WARM Background and Overview chapter.

The recycling GHG emission factors are provided in the chapters corresponding to each individual material modeled in WARM. These GHG emission factors represent the GHG emissions associated with recycling each material into a new product for use, minus a GHG emission offset for avoiding the manufacture of an equivalent amount of the product from virgin inputs.

In evaluating the relative GHG reduction benefits of recycling compared to an existing materials management practice (i.e., evaluating the benefits of recycling relative to source reduction, composting, combustion or landfilling), the recycling GHG emission factors developed in WARM must be compared against the corresponding emission factors for the existing management practice. For example, to evaluate the GHG emission reductions from recycling one short ton of aluminum cans instead of sending the same quantity to the landfill, the GHG emission factor for landfilling one short ton of aluminum cans must be subtracted from the recycling emission factor for aluminum cans. Please see the WARM Background and Overview chapter for additional explanation of the comparative aspect of WARM emission factors.

## 2. RESULTS

The national average results of this analysis are shown in Exhibit 2. The net GHG emission reductions from recycling of each material are shown in column (f). As stated earlier, these estimates of net GHG emissions are expressed for recycling in absolute terms, and are not values relative to another waste management option, although they must be used comparatively, as all WARM emission factors must be. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

**Exhibit 2: Emission Factor for Recycling ($MTCO_2E$/Short Ton of Material Recovered)**

| (a) Material | (b) Recycled Input Credit:[a] Process Energy | (c) Recycled Input Credit:[a] Transportation Energy | (d) Recycled Input Credit:[a] Process Non-Energy | (e) Forest Carbon Storage | (f) GHG Reductions from Using Recycled Inputs Instead of Virgin Inputs (f = b + c + d + e) |
|---|---|---|---|---|---|
| Aluminum Cans | -5.35 | -0.04 | -3.72 | – | -9.11 |
| Aluminum Ingot | -3.98 | -0.03 | -3.18 | – | -7.19 |
| Steel Cans | -1.77 | -0.04 | 0.00 | – | -1.81 |
| Copper Wire | -4.67 | -0.06 | 0.00 | – | -4.72 |
| Glass | -0.12 | -0.02 | -0.14 | – | -0.28 |
| HDPE | -0.71 | – | -0.17 | – | -0.88 |

| (a)<br><br>Material | (b)<br><br>Recycled Input Credit:[a] Process Energy | (c)<br><br>Recycled Input Credit:[a] Transportation Energy | (d)<br><br>Recycled Input Credit:[a] Process Non-Energy | (e)<br><br>Forest Carbon Storage | (f)<br>GHG Reductions from Using Recycled Inputs Instead of Virgin Inputs<br>(f = b + c + d + e) |
|---|---|---|---|---|---|
| LDPE | NA | NA | NA | NA | NA |
| PET | -0.88 | 0.09 | -0.34 | 0.00 | -1.13 |
| LLDPE | NA | NA | NA | NA | NA |
| PP | NA | NA | NA | NA | NA |
| PS | NA | NA | NA | NA | NA |
| PVC | NA | NA | NA | NA | NA |
| PLA | NA | NA | NA | NA | NA |
| Corrugated Containers | -0.003 | -0.05 | -0.01 | -3.06 | -3.12 |
| Magazines/Third-Class Mail | -0.01 | – | – | -3.06 | -3.07 |
| Newspaper | -0.70 | -0.03 | – | -2.02 | -2.75 |
| Office Paper | 0.21 | – | -0.02 | -3.06 | -2.86 |
| Phone Books | -0.62 | – | – | -2.02 | -2.64 |
| Textbooks | -0.05 | – | – | -3.06 | -3.11 |
| Dimensional Lumber | 0.07 | 0.01 | – | -2.53 | -2.46 |
| Medium-Density Fiberboard | 0.05 | 0.02 | – | -2.53 | -2.47 |
| Food Waste | NA | NA | NA | NA | NA |
| Food Waste (meat only) | NA | NA | NA | NA | NA |
| Food Waste (non-meat) | NA | NA | NA | NA | NA |
| Beef | NA | NA | NA | NA | NA |
| Poultry | NA | NA | NA | NA | NA |
| Grains | NA | NA | NA | NA | NA |
| Bread | NA | NA | NA | NA | NA |
| Fruits and Vegetables | NA | NA | NA | NA | NA |
| Dairy Products | NA | NA | NA | NA | NA |
| Yard Trimmings | NA | NA | NA | NA | NA |
| Grass | NA | NA | NA | NA | NA |
| Leaves | NA | NA | NA | NA | NA |
| Branches | NA | NA | NA | NA | NA |
| Mixed Paper | | | | | |
| Mixed Paper (general) | -0.36 | -0.11 | -0.01 | -3.06 | -3.53 |
| Mixed Paper (primarily residential) | -0.36 | -0.11 | -0.01 | -3.06 | -3.53 |
| Mixed Paper (primarily from offices) | -0.42 | -0.11 | -0.001 | -3.06 | -3.59 |
| Mixed Metals | -3.03 | -0.04 | -1.31 | – | -4.38 |
| Mixed Plastics | -0.81 | 0.06 | -0.28 | – | -1.03 |
| Mixed Recyclables | -0.22 | -0.03 | -0.07 | -2.50 | -2.83 |
| Mixed Organics | NA | NA | NA | NA | NA |
| Mixed MSW | NA | NA | NA | NA | NA |
| Carpet | -1.41 | -0.01 | -0.94 | – | -2.36 |
| Personal Computers | -1.59 | -0.04 | -0.88 | – | -2.51 |
| Clay Bricks | NA | NA | NA | NA | NA |
| Concrete | -0.001 | -0.01 | – | – | -0.01 |
| Fly Ash | -0.42 | – | -0.45 | – | -0.87 |
| Tires | -0.46 | 0.07 | – | – | -0.39 |
| Asphalt Concrete | -0.03 | -0.05 | – | NA | -0.08 |
| Asphalt Shingles | -0.11 | 0.01 | – | NA | -0.09 |
| Drywall | 0.01 | 0.02 | – | – | 0.03 |
| Fiberglass Insulation | NA | NA | NA | NA | NA |
| Vinyl Flooring | NA | NA | NA | NA | NA |

| (a) Material | (b) Recycled Input Credit:[a] Process Energy | (c) Recycled Input Credit:[a] Transportation Energy | (d) Recycled Input Credit:[a] Process Non-Energy | (e) Forest Carbon Storage | (f) GHG Reductions from Using Recycled Inputs Instead of Virgin Inputs (f = b + c + d + e) |
|---|---|---|---|---|---|
| Wood Flooring | NA | NA | NA | NA | NA |

NA = Not applicable. For the plastic resin material types, only HDPE and PET recycling are modeled in WARM due to LCI data availability.
– = Zero emissions.
Note that totals may not add due to rounding, and more digits may be displayed than are significant. Negative values denote GHG emission reductions or carbon storage.
[a] Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing and remanufacturing. Recycling credit is based on closed- and open-loop recycling, depending on material.

## 3. LIMITATIONS

The data presented in this document involve GHG emissions associated with the raw materials and acquisition of materials; therefore, the limitations related to raw materials and acquisition for specific material types are provided in respective material type chapters. Other limitations are as follows:

- The recycling results are reported in terms of GHG emissions per short ton of material collected for recycling. Thus, the emission factors incorporate assumptions on loss of material through collection, sorting and remanufacturing. There is uncertainty in the loss rates: some materials recovery facilities and manufacturing processes may recover or use recycled materials more or less efficiently than as estimated here.
- Because the modeling approach assumes closed-loop recycling for most materials, it does not fully reflect the prevalence and diversity of open-loop recycling. Most of the materials in the analysis are recycled into a variety of manufactured products, not just into the original material. Resource limitations prevent an exhaustive analysis of all of the recycling possibilities for each of the materials analyzed.
- For the purpose of simplicity, EPA assumed that increased recycling does not change overall demand for products. In other words, it was assumed that each incremental short ton of recycled inputs would displace virgin inputs in the manufacturing sector. In reality, there may be a relationship between recycling and demand for products with recycled content, since these products become cheaper as the supply of recycled materials increases.

## 4. REFERENCES


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