Waste Reduction Model (WARM)

Data Quality Assessment Report

U.S. Environmental Protection Agency
Office of Land and Emergency Management
Office of Resource Conservation & Recovery

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Acronyms and Abbreviations

C&D	Construction and demolition
DQ	Data quality
DQA	Data Quality Assessment
DQG	Data Quality Goal
DQI	Data Quality Indicator
DQS	Data Quality System
EPA	U.S. Environmental Protection Agency
GHG	Greenhouse gas
HDPE	High-density polyethylene
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MSW	Municipal solid waste
ORD	EPA Office of Research and Development
PET	Polyethylene terephthalate
PP	Polypropylene
PVC	Polyvinyl chloride
WARM	Waste Reduction Model

Executive Summary

This report describes the findings from the detailed assessment of the quality of the data used to develop the greenhouse gas (GHG) emission and energy factors in the U.S. Environmental Protection Agency's (EPA) Waste Reduction Model (WARM).[1] The purpose of this effort is to support EPA in understanding and improving the data quality in WARM, and to provide additional transparency and insight on the underlying data for WARM users. The report also offers recommendations for prioritizing future updates.

This data quality assessment (DQA) involved a comprehensive review of the datasets used in the WARM modeling for each material type and materials management pathway. The data quality for each data source used to develop the WARM GHG emission and energy factors was evaluated for each of the flow and process indicators described in EPA's "Guidance on Data Quality Assessment for Life Cycle Inventory Data" (Edelen and Ingwersen 2016). Flow indicators consider the reliability of the measurements, and the correlation of the age of data, geographical coverage, and technological representativeness with the study's data quality goals. Process indicators consider the data review process used and the completeness of the dataset.

The calculation of averages for each indicator grouping and for each material type and pathway facilitated the assessment of the overall data quality for a material category or management pathway—particularly across the large number of datasets and over 60 material types. Average scores were translated into data quality levels, ranging from low to high. To give additional weight to the key data sources driving emission and energy factor estimates for a material category, weighted average scores also were calculated along with average scores.

[1] Available at https://www.epa.gov/warm.

Table 1 summarizes findings on data quality for the data quality indicator groupings by material category and management pathway. The shading offers a big picture heat-map-like view of the data quality findings with darker shading indicating higher data quality and lighter shading indicating lower data quality. The report provides detail on these data quality results, and the Appendix: Data Quality Assessment Matrix. This Appendix presents the scoring details in a matrix form by material, management pathway, and dataset.

Table 1: **Summary of Data Quality Results by Material Type or Management Pathway**

Material or Pathway	DQ Values by Indicator Grouping				
	Flow Reliability[a]	Flow Represent-ativeness[b]	Process Review and Completeness[c]	Average[d]	Weighted Average[e]
Material Category					
Plastics	Medium-high	Medium-high	Medium	**Medium-high**	**Medium-high**
Bioplastics	Medium-high	Medium	Medium-high	**Medium-high**	**Medium-high**
Metals	Medium	Medium	Medium	**Medium**	**Medium**
Glass	Medium	Medium	Medium	**Medium**	**Medium-low**
Paper	Medium-low	Medium	Medium-low	**Medium-low**	**Medium**
Electronics	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Construction Materials	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Asphalt Concrete	*Medium-high*	*Medium*	*Medium-high*	***Medium-high***	***Medium***
Asphalt Shingles	*Medium-low*	*Medium*	*Medium*	***Medium***	***Medium***
Carpet	*Medium*	*Medium-low*	*Medium-low*	***Medium-low***	***Medium***
Clay Bricks	*Medium-high*	*Medium-high*	*High*	***Medium-high***	***High***
Concrete	*High*	*Medium-high*	*Medium*	***Medium-high***	***Medium-high***
Dimensional Lumber	*Medium-high*	*Medium-high*	*High*	***Medium-high***	***Medium-high***
Drywall	*Medium-high*	*Medium-high*	*Medium-high*	***Medium-high***	***Medium-high***
Fiberglass Insulation	*Medium*	*Medium*	*Medium*	***Medium***	***Medium***
Fly Ash	*Medium-high*	*Medium-high*	*Medium*	***Medium-high***	***Medium-high***
Medium-density Fiberboard	*Medium-high*	*Medium-high*	*High*	***Medium-high***	***Medium-high***
Structural Steel	*Medium-high*	*Medium-high*	*Medium-high*	***Medium-high***	***Medium-high***
Vinyl Flooring	*Medium-high*	*Medium*	*Medium-high*	***Medium***	***Medium***
Wood Flooring	*Medium-high*	*Medium*	*Medium-high*	***Medium-high***	***Medium-high***
Tires	Medium	Medium	Medium	**Medium**	**Medium**
Food Waste (non-meat)	Medium-high	Medium	Medium-high	**Medium**	**Medium**
Food Waste (meat)	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Yard Trimmings	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Management Pathway[f]					
Landfilling	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Composting	Medium-high	Medium	High	**Medium-high**	**Medium-high**
Combustion	Medium	Medium-low	Medium	**Medium**	**Medium**
Anaerobic Digestion	Medium-high	Medium	Medium-high	**Medium-high**	**Medium**

[a]Refers to data generation method and verification.
[b]Includes temporal correlation (data year), geographical correlation (region of data), technological correlation (technology type, scale), and data collection methods (representativeness, sample size).
[c]Includes process review (third party or internal reviewers) and process completeness (percent of flows covered).
[d]Average of all indicators.
[e]Developed to give additional weight to the key data sources informing the emission factor estimates.
[f]Separate data quality assessments for source reduction and recycling were not conducted as their data sources were already captured under the material-specific data assessments.

Key findings from this assessment include the following:

- **Overall results:** The average and weighted average[2] data quality levels for the WARM data sources were assessed to be medium to medium-high for most material categories and management pathways.
- **Results by material category:** Based on the weighted average of data quality results across the indicators, medium-high data quality was found for plastics, bioplastics, electronics, construction materials, food waste (meat), and yard trimmings; medium quality was found for metals, paper, food waste (non-meat), and tires; and medium-low for glass. Within the construction materials category, data quality results ranged from medium for asphalt concrete, asphalt shingles, carpet, fiberglass insulation, and vinyl flooring to high data quality for bricks.
- **Results by management pathway:** Based on the weighted average of data quality results across the indicators, medium-high data quality was found for landfilling and composting, and medium for combustion and anaerobic digestion.
- **Results by indicator:** Process review and completeness generally had the highest data quality. While several data sources had lower data quality for the temporal correlation indicator (a sub-category of flow representativeness) due to age of data, this did not lead to low overall data quality due to the other data quality considerations.

This assessment informed the following recommendations:

- Identify more recent data sources for select materials.
- Identify published data sources to update certain data inputs.
- Prioritize updates to the modeling of glass, paper, metals, food waste (non-meat), carpet, asphalt shingles, fiberglass insulation, vinyl flooring, tires, and combustion.
- Improve the archiving and accessibility of the underlying data sources.
- Communicate the DQA findings alongside the WARM documentation.

[2] Considers additional weighting for key data sources used in a particular category.

1. Introduction

The U.S. Environmental Protection Agency's (EPA) Waste Reduction Model (WARM) is a tool for estimating the life-cycle greenhouse gas (GHG) emission, energy, and economic impacts of various materials commonly found in municipal solid waste (MSW) under baseline and alternative waste management scenarios. Currently, the model includes over 60 different materials and the materials management pathways of source reduction, recycling, composting, combustion, landfilling, and anaerobic digestion. EPA first developed WARM as a way to quantify the connection between waste management practices and climate change, and to determine the potential for source reduction and recycling of MSW to reduce GHG emissions. The first documentation report applying the WARM GHG and energy factors, entitled *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, was published in 1998. At the time, WARM included 17 material types commonly found in MSW. Since then, EPA has expanded the model to include dozens of additional material types, incorporated more sophisticated modeling of the management practice pathways, added the anaerobic digestion pathway, quantified economic impacts, and made many other updates and improvements. In addition, EPA organized the WARM documentation into chapters by material and pathway to provide WARM users with detailed information about the specific materials analyzed in WARM and the calculations behind the specific material emission, energy, and economic factors in the model. The currently available online Excel version of the tool is version 15 available at epa.gov/warm.

WARM relies on numerous data sets for the development of material-specific GHG emission, energy, and economic factors.[3] This report summarizes the detailed review of the data sources behind WARM and an analysis of the quality of the data used to develop the emission and energy factors in the model. The purpose of this effort is (a) to support EPA in understanding and improving upon the data quality in WARM and prioritizing future updates, and (b) to provide additional transparency and insight on the underlying data for WARM users. This effort is intended to shed light on areas for data quality improvement, particularly across the numerous and diverse data sets used to develop WARM's factors.

Importance of Data Quality to EPA

Data quality is critically important to EPA's programs. Understanding and maintaining the quality of data is a crucial aspect of the EPA's scientific process, as outlined in the EPA Order CIO 2105.0 policy on mandatory agency-wide quality systems (EPA 2000). EPA recognizes that low quality datasets or values can in turn affect the integrity of values that rely on that data. Through a comprehensive assessment of data quality, EPA seeks to advance the understanding of data quality, increase transparency, and ultimately improve upon the data quality. Federal legislation is driving EPA and other federal agencies to prioritize data accessibility. The *Foundations for Evidence-Based Policymaking Act of 2018* mandates that agencies such as the EPA improve the accessibility of data and use statistical evidence in the development of policies and evaluation plans (H.R.4174 – 115th Congress 2017-2018). EPA implements internal guidelines to guarantee the collection of data is done correctly and the quality of the data is

[3] The methodology used to develop the WARM emission, energy, and economic factors is detailed in the WARM Documentation, available at https://www.epa.gov/warm/documentation-waste-reduction-model-warm#documentation.

maintained. These regulations and guidelines exist to establish the credibility and trust of the information produced by EPA and other federal agencies.

As part of the agency's efforts to prioritize and carry-out data quality improvements, EPA has invested in the development of guidance on data quality assessments and comprehensive evaluations of the quality of data used in its analyses and programs. EPA's Office of Research and Development (ORD) developed a systematic methodology for data quality assessment (DQA) for life cycle inventory (LCI) data. This approach is detailed in the "Guidance on Data Quality Assessment for Life Cycle Inventory Data" (ORD Guidance) and discussed in further detail in the following Approach section (Edelen and Ingwersen 2016). Life cycle assessments (LCA), which evaluate environmental impacts across the life stages of a material, product, or system, rely on many data inputs. LCA practitioners often use different methodologies, tools, and approaches for documentation, and assessment of data quality can become subjective. The ORD Guidance helps standardize the data quality review process to improve objectivity in the scoring process, allowing for reproducibility of data quality scores, and improving understanding of LCI data quality.

What is a Data Quality Assessment?

A data quality assessment (DQA) is a systematic review of a data source to determine its reliability and level of quality as it relates to the goal and scope of the study or analysis. Rather than deeming a data source good or bad, a DQA conducts a multi-pronged review based on several key analysis points. For this DQA, each data source was reviewed based on several flow and process indicators. Flow indicators consider the reliability of the measurements, and the correlation of the age of data, geographical coverage, and technological representativeness with the study's data quality goals (DQGs). Process indicators consider the data review process used and the completeness of the dataset. As noted in the ORD Guidance, the goal of a DQA with the use of a pedigree matrix scoring approach is to "see where potential data quality issues might exist within large datasets and/or models with multiple processes" (Edelen and Ingwersen 2016).

In understanding the results from a DQA, it is important to recognize a few key elements:

- Certain data quality results are static, while others are dynamic. Reliability of the data, based on how the data were developed, is a static, unchanging, data quality element. Temporal correlation is a dynamic data quality element that will change depending on a user's timeframe of study and the strength of a dataset's correlation will change with the passing of time.

- A DQA may not capture all data sources or all data quality elements. Certain data may be unavailable or inaccessible. Other data may be unknown to a data developer or may not be possible to quantify.

- The user dimension is an important piece of how data quality results are interpreted. The data quality can help inform how data are used by a particular user or for a specific purpose (e.g., for certain uses or applications, a lower data quality dataset may be sufficient). In addition, while a data developer is responsible for documenting and clearly communicating data quality elements, a data user is responsible for assessing the appropriateness of the applications and uses of the data.

In the case of WARM, users of the tool and the emission and energy factors need to be aware that the development of the factors includes multiple data sources and assumptions. This report describes the data sources and assesses the quality of each of the data sets, to the extent feasible. A concerted attempt was made to include all known data sources used for the emission and energy factor development. The WARM documentation chapters[4] provide additional detail on the data sources and discuss the boundaries of the analysis, the methodologies used to develop the factors, and limitations related to the modeling of the emissions and energy use for the various material categories and management practices.

The remainder of this report is organized as follows:

- **Section 2:** Approach
- **Section 3:** Assessment of Material Datasets
- **Section 4:** Assessment of Specific Management Pathway Datasets
- **Section 5**Error! Reference source not found.**: Error! Reference source not found.**Conclusion
- **References**
- **Appendix:** Data Quality Assessment Matrix

2. Approach

The scope of this assessment focused on the data used to develop the greenhouse gas (GHG) emission and energy factors in EPA's Waste Reduction Model (WARM). The factors are built with life-cycle inventory and assessment data from various sources with a focus on prioritizing publicly available, peer-reviewed reports, literature, and databases. The approach used for the data quality assessment (DQA) follows that described in the "Guidance on Data Quality Assessment for Life Cycle Inventory Data" developed by EPA's Office of Research and Development (ORD Guidance) (Edelen and Ingwersen 2016). The ORD Guidance specifies data review elements at the flow and process levels. The flow level indicators cover reliability and representativeness of the data, and the process level indicators cover the review process and completeness of the dataset.

The ORD Guidance provides data quality indicators (DQIs) to accurately assess the "functionality of data within the boundaries of a particular study or project goal and scope" for life cycle inventory (LCI) data. The guidance not only provides detailed information on the relevance and applicability of each identified DQI, but also provides direction for developing a pedigree matrix data quality system (DQS) with objective and clear scoring parameters. The DQA process involves scoring of five flow indicators and two process indicators, as described in Table 2.

[4] Available at https://www.epa.gov/warm.

Table 2: Indicators Used for Assessing and Scoring the Quality of Data Sources

Indicator	Description
Flow Indicators	
Flow Reliability	Used for reviewing if measurements and calculations in a source are verified and reliable.
Temporal Correlation	Used for measuring the age difference between the temporal data quality goal (DQG) and the data generation date in a source.
Geographical Correlation	Used for reviewing the relationship between the geographical DQG and the area of study in a source.
Technological Correlation	Used for reviewing the relationship between the technological DQG and the technological approach in a source. There are four categories of technological representativeness reviewed by this indicator: process design, operating conditions, material quality, and process scale. More information on these categories can be found in the Appendix.
Data Collection Methods/ Representativeness	Used for identifying if a significant percentage of the relevant market share of an industry is covered over an adequate time period by a source.
Process Indicators	
Process Review	Used for identifying if a source has been reviewed by adequate third-party reviewers and if proper documentation of the review accompanies the data in a source.
Process Completeness	Used for identifying the percentage of flows determined for a process that has been evaluated and assigned a value in a source.

The scoring for each indicator, as described in the ORD Guidance, ranges from 1-5 with the lowest score, 1, representing the highest quality data. A lower cumulative score or average score of all indicators represents a data source with high quality data and methodology, whereas a higher score indicates poorer data quality. The Data Quality Pedigree Matrix with the scoring range descriptions for each flow and process DQI from the ORD Guidance is presented in Table 3.

Table 3: Data Quality Pedigree Matrix for Flow and Process Indicators

Highest data quality ⟵⟶ Lowest data quality

Indicator		1	2	3	4	5
Flow Indicators						
Flow Reliability		Verified data based on measurements[a]	Verified data based on a calculation **or** non-verified data based on measurements	Non-verified data based on a calculation	Documented estimate	Undocumented estimate
Flow Representativeness	**Temporal Correlation**	Less than 3 years of difference[b]	3 to 6 years of difference	Less than 10 years of difference	Less than 15 years of difference	Age of data unknown or more than 15 years
Flow Representativeness	**Geographical Correlation**[c]	Data from same resolution **and** same area of study	Within one level of resolution **and** a related area of study	Within two levels of resolution **and** a related area of study	Outside of two levels of resolution **but** a related area of study	From a different or unknown area of study
Flow Representativeness	**Technological Correlation**[d]	All technology categories are equivalent	**Three** of the technology categories are equivalent	**Two** of the technology categories are equivalent	**One** of the technology categories is equivalent	**None** of the technology categories are equivalent
Flow Representativeness	**Data Collection Methods**	Representative data from >80% of the relevant market[e], over an adequate period of time[f]	Representative data from 60-79% of the relevant market, over an adequate period **or** representative of data from >80% of the relevant market, over a shorter period of time	Representative data from 40-59% of the relevant market, over an adequate period of time **or** representative data from 60-79% of the relevant market, over a shorter period of time	Representative data from <40% of the relevant market, over an adequate period of time **or** representative data from 50-59% of the relevant market, over a shorter period of time	Unknown **or** data from a small number of sites **and** from shorter periods
Process Indicators						
Process Review		Documented reviews by a minimum of two types[g] of third-party reviewers	Documented reviews by a minimum of two types of reviewers, with one being a third party	Documented review by a third-party reviewer	Documented review by an internal reviewer	No documented review
Process Completeness		>80% of determined flows have been evaluated and given a value	60-79% of determined flows have been evaluated and given a value	40-59% of determined flows have been evaluated and given a value	<40% of determined flows have been evaluated and given a value	Process completeness not scored

[a] Verification may take place in several ways, e.g., by on-site checking, by recalculation, through mass balances or cross checks with other sources. For values calculated from a mass balance or another verification method, an independent verification method must be used to qualify the value as verified.

[b] Temporal difference refers to the difference between date of data generation and the date of representativeness as defined by the scope of the project.

[c] Geographical representativeness for this study set is based on EPA data quality goals of national data 1: U.S. data, national in scope; 2: U.S. data, state or local level in scope; 3: North American data; 4: Global data; 5: Unknown location of data.

[d] Technological categories are process design, operating conditions, material quality, and process scale.

[e] The relevant market should be documented in the DQG. The default relevant market is measured in production units. If the relevant market is determined using other units, this should be documented in the DQG. The relevant market established in the metadata should be consistently applied to all flows within the unit.

[f] Adequate time period can be evaluated as a time period long enough to even out normal fluctuations. The default time period is 1 year, except for emerging technologies (2-6 months) or agricultural projects >3 years.

[g] Types are defined as either industry or LCA experts.

Following the ORD Guidance and using the DQIs described above, this assessment involved the following steps:

- **Step 1: Review of WARM DQGs:** To ensure a systematic review of the various datasets, the process began with a review of the DQGs for an ideal WARM dataset as they align with the various DQIs. These WARM DQGs are outlined in **Error! Reference source not found.** below:

Table 4: WARM Data Quality Goals Aligned to the Indicators

Indicator		WARM Goal
Flow Indicators		
Flow Reliability		Documented data are ideally verified by in-person authentication or repeatable calculation measurements.
Flow Representativeness	**Temporal Correlation**	Temporal correlation with data collected, measured, or estimated as recent as possible to the present without compromising in the other data quality areas.
	Geographical Correlation	Data represent U.S. conditions at the national level.
	Technological Correlation	Strong technological correlation to the process or technology addressed for each material or management pathway, with clear information on inputs. Studies should ideally reflect the current processes employed by the market.
	Data Collection Methods	Representative of the majority of the market over a reasonable period of time to avoid outlying data, ideally within one year.
Process Indicators		
Process Review		Data are reviewed by at least one third-party reviewer, ideally multiple.
Process Completeness		Majority of the determined flows evaluated in the LCI datasets.

- **Step 2: Creation of a DQA Review Matrix**: A comprehensive data quality review matrix in Excel covering the DQIs within the ORD Guidance was created and used to review each dataset in a systematic way.

- **Step 3: Identification of Data Elements and References**: Multiple data sources are used to develop the emission and energy factors for each material type in WARM. For this DQA effort, each material type and management pathway in WARM, the key unit process data elements and corresponding data sources and source years were identified. To do so, each source referenced in the WARM documentation and emission and energy factor calculations spreadsheet used to develop the latest version of WARM was included in the DQA review matrix.

- **Step 4: Collection of the Data Sources:** The ORD Guidance describes the importance of using and assessing the original documentation. The original data sources for each data element as referenced in the WARM documentation were identified and gathered to the extent feasible within archives. As part of this effort, a comprehensive archive of the underlying data resources by material category and end-of-life pathway was created. A few sources for specific material types and management pathways could not be located, particularly documentation of prior conversations with industry experts. These sources were given the lowest data quality scores.

➢ **Step 5: Review of Data Sources and Scoring Assessment of Data Quality**: The gathered data sources were reviewed against the different DQIs and the data quality findings were noted. For each data source, each indicator was scored based on the ORD Guidance criteria in Table 3 and the totals across the indicators were summed to obtain a total score, ranging from 7 (highest quality) to 35 (lowest quality). The average across the indicators was also taken and ranged from 1 to 5. For an example of this process, a plastic data source received the scores shown in Table 5 for the five flow indicators and two process indicators, which sum to the total score of 16 and average to 2.3.

Table 5: Example of DQ Scoring Assessment for a Single Data Source

Flow Indicators					**Process Indicators**			
	Flow representativeness							
Flow Reliability	**Temporal correlation**	**Geographical correlation**	**Technological correlation**	**Data collection methods**	**Process Review**	**Process Completeness**		
Data generation method & verification	**Data year**	**Region of data**	**Technology type, scale**	**Representativeness, sample size**	**Third party or internal reviewer(s)**	**% of flows covered**	**Total Score**	**Average Score**
1	5	1	2	1	5	1	**16**	**2.3**

To give additional weight to the key data sources driving emission and energy factor estimates for a material category, a weighted average score was calculated along with an average score. While the average score takes the total score for all data sources and divides by the number of sources for each material type, the weighted average redistributes the weight of each study's score based on whether the data source is a driving factor in overall emissions. For example, a source was generally considered key if it impacts several materials within a category, is a lead source in process emission estimates, or is comprehensive enough to be used throughout the life cycle of a material's emission estimates. In the weighted average score, key sources were given double the weight of other, non-key sources.

➢ **Step 6: Alignment of Scores with Data Quality Levels**: Across multiple data sources for a material category or pathway, the averages for high level indicators of flow reliability, flow representativeness, and process review and completeness were taken and used to develop average data quality values across that material category or pathway. The averaged data quality values were aligned with data quality levels from low to high as shown in Table 6. To present the results in a more visual way, a shading system was applied to the scores where pale blue was assigned to the lowest data quality level with an average data quality value of one and dark blue was assigned to the highest data quality level corresponding with an average data quality value of five. Between those data quality levels and values the shading scales from light blue for low data quality to dark blue for high data quality. In the case of the example data source above, the average score of 2.3 aligned with a data quality level of medium-high.

Table 6: Alignment of Average Data Quality Values with Data Quality Levels

Average DQ Value	DQ Levels
1	High
2	Medium-high
3	Medium
4	Medium-low
5	Low

- **Step 7: Assessment of Results**: Based on the scoring assessment, the resulting matrix was organized into the categories – high, medium-high, medium, medium-low, and low data quality scores. For each material category and management pathway the following summary table is presented in the sections that follow.

Management Pathway	DQ Values by Indicator Grouping				
	Flow Reliability[a]	Flow Represent-ativeness[b]	Process Review and Completeness[c]	Average[d]	Weighted Average[e]

[a]Refers to data generation method and verification.
[b]Includes temporal correlation (data year), geographical correlation (region of data), technological correlation (technology type, scale), and data collection methods (representativeness, sample size).
[c]Includes process review (third party or internal reviewers) and process completeness (percent of flows covered).
[d]Average of all indicators.
[e]Developed to give additional weight to the key data sources informing the emission factor estimates.

The materials or pathways with datasets receiving the lowest data quality scores and the indicators contributing to those scores were identified and will require closer examination to inform prioritization of future WARM updates.

- **Step 8: Preparation of Findings and Recommendations**: This report was developed to summarize key findings, areas for improvement, and recommendations for addressing WARM's data quality. Weighted averages were calculated to provide additional context to the reader and give a deeper view into how different data sources were used. These weighted averages could also be used in the future to help prioritize updates to source materials.

3. Assessment of Material Datasets

The following sections present the results from the assessment of the quality of the datasets and data sources by material category (e.g., metals) and type (e.g., aluminum cans). Summaries of key findings are presented followed by recommended areas for further research and improvement of the data quality. In the discussion of data sources, key sources used in the development of the emission and energy factors are noted as **(KEY)**. They are weighted more heavily for the development of the weighted averages. Additional details on the scoring results from the assessment of the flow level and process level indicators for each material data source are presented in the Appendix: Data Quality Assessment Matrix.

3.1 Plastics and Bioplastics

Summary of Key Findings

Data Sources. WARM includes emission and energy factors for seven plastic resins—high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), linear low-density polyethylene (LLDPE), polypropylene (PP), general purpose polystyrene (GPPS), and polyvinyl chloride (PVC)—a mixed plastics category, and the bioplastic, polylactide (PLA) biopolymer resin. The development of the factors relied on the use of both key sources and additional sources, as described below.

The primary data sources used to develop the fossil-based plastic resin factors include:

- The Life-Cycle Inventory (LCI) report, *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors* (FAL 2011), which provides raw material acquisition and manufacturing energy data for the production of the virgin plastic resins HDPE, LDPE, PET, LLDPE, PP, GPPS, and PVC. This report presents a cradle-to-gate LCI quantifying the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of nine plastic resins produced in North America. **(KEY)**

- The LCI report, *Life Cycle Impacts for Postconsumer Recycled Resins: PET, HDPE, and PP* (FAL 2018), which provides process energy data for the production of recycled plastics resins HDPE, PET, and PP. This report presents a cradle-to-gate life cycle analysis quantifying total emissions from the production of recycled HDPE, PET, and PP resins in North America. **(KEY)**

The bioplastics factors rely largely on two primary data sources:

- The NatureWorks U.S. LCI spreadsheet entitled *"SS Polylactide Biopolymer Resin_US LCI May_2010.xls"* submitted to the U.S. LCI Database[5] (U.S. LCI 2010). It provides raw material acquisition and manufacturing energy data for the production of Ingeo PLA resin. Although this source reflects PLA resin production by NatureWorks LLC in Blair, Nebraska, it is considered representative of U.S. PLA production due to the absence of direct competitors to NatureWorks operating a fully industrial-scale PLA manufacturing plant in the United States. **(KEY)**

- Responses from NatureWorks on ICF's preliminary review of the NatureWorks PLA LCI Data Memo (NatureWorks 2010). The responses include updated data for net atmospheric CO_2 uptake during corn production, landfill carbon storage, and PLA carbon content. **(KEY)**

Transportation-related information was obtained from the following data sources:

- For all plastics resins and bioplastics: *US Census Commodity Flow Survey Preliminary Tables, Table 1: Shipment Characteristics by Mode of Transportation for the United States* (BTS 2013). This source is a Commodity Flow Survey (CFS) on domestic freight shipments developed jointly

[5] U.S. Life Cycle Inventory Database | NREL, https://www.nrel.gov/lci/

by the Bureau of Transportation Services (BTS), the U.S. Census Bureau, and U.S. Department of Commerce. It provides data on retail transportation distance and fuel-type.

- For bioplastics: *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (FAL 1994). This report is a study on the role of recycling in integrated solid waste management published by Franklin Associates and provides data on transportation energy use.

- For bioplastics: *Evaluation of Climate, Energy, and Soils Impacts of Selected Food Discards Management Systems* (Oregon Department of Environmental Quality [DEQ] 2014). This report evaluates the environmental and energy impacts of specific food discards management systems and provides data on transportation emissions. The transportation emissions data from this report are used for bioplastics.

Scoring. The average DQA scores for plastics and bioplastics varied within the medium to medium-high data quality levels. A summary of the results by data quality indicator grouping for plastics and bioplastics is shown in Table 7. The key findings for each of the sources used for plastics and bioplastics are discussed below.

Table 7: Summary of Data Quality Results for Plastics and Bioplastics Data Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	**Flow Representativeness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Plastics	Medium-high	Medium-high	Medium	**Medium-high**	**Medium-high**
Bioplastics	Medium-high	Medium	Medium-high	**Medium-high**	**Medium-high**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Plastics

The medium-high data quality average and weighted average for the fossil-based plastic resins was largely a consequence of the data from the virgin plastic resin LCI report (FAL 2011) reflecting medium-high and high data quality for most flows and process indicators. The exception for that data source is the process review indicator (a sub-category of the process review and completeness indicators), which was deemed low quality due to lack of information on external reviews in that report and temporal correlation (a sub-category of the flow representativeness indicator), which reflects medium-low data quality due to the data used in FAL (2011) being representative of 2003 or earlier. The recycled plastic resin LCI report (FAL 2018) was classified as medium to high data quality across the indicators as it covers over 80 percent of processes in North America related to the emissions of recycling plastics, with a representative data pool and documented calculation. The Role of Recycling Report (FAL 1994), which provides general transportation equipment information, was determined to be of medium-high data quality as it characterizes a majority of the municipal solid waste in the United States at the time, uses calculated data, and covers a wide scope of technologies, including vehicle type, vehicle load, and material type to inform data on transportation equipment. However, FAL (1994) is not a higher data quality source due to low quality temporal correlation as the data were collected in 1992. This likely impacts the validity of the data as transportation technology has changed since 1992. The Commodity Flow Survey (BTS 2013) reflects medium data quality overall, as it was characterized as medium-low data quality for temporal correlation and process review due to data that are over 10 years old and a lack of information on external reviews. The source also reflected low data quality for process completeness (sub-category of process review and completeness indicators).

The plastic data sources generally reflect high data quality for flow reliability, geographical correlation, and data collection (sub-categories of the flow representativeness indicators), and process completeness indicators. However, the plastic data sources reflect low data quality for the temporal correlation indicator (sub-category of the flow representativeness indicators) and process review indicator. The mixed plastics material type in WARM is the average of the emission factors developed for the plastic resins. Therefore, the average plastics data quality scoring was applied to assess the “mixed plastics” material category.

Bioplastics

For bioplastics, the NatureWorks LCI dataset (U.S. LCI 2010) was characterized as having medium-high to high data quality across the indicators, with the exception of the temporal correlation indicator, which reflected medium-low quality. The additional NatureWorks source (Vink 2010) is of medium-high data quality overall, as it was deemed high quality across most indicators, but low data quality for temporal correlation and process review completeness (sub-category of process review and completeness indicators) as it is a relatively old source and lacks documentation of external reviews. The data quality of the additional data sources—BTS (2013), FAL (1994), Oregon DEQ (2014)—used for the PLA emission and energy factors are described above under plastics.

Overall, the plastics datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Overall, the bioplastics datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Recommendations

Areas for improvement include:

- Identify and incorporate an additional source for raw material acquisition and manufacturing energy data for the production of virgin plastic resins that has two or more types of documented third-party reviews. The current source, FAL (2011), that provides process energy data for all virgin plastic resins does not have any documented third-party reviews.
- Identify and incorporate an additional source for plastics with process data for production of additional recycled plastic resins (i.e., LDPE, LLDPE, GPPS, and PVC). FAL (2018), the singular source for data on recycled plastic resins, includes only HDPE, PET, and PP resins.
- Update the retail transportation distance and fuel-type information with the more recently available US Census Commodity Flow Survey (from 2017).

3.2 Metals

Summary of Key Findings

Data Sources. The types of metals modeled in WARM include aluminum cans, aluminum ingot, steel cans, and copper wire. This WARM material category focuses on container and packaging end-uses for aluminum and steel and electrical end-uses for copper wire. Metals can be employed in various sectors and products; other major uses of aluminum in addition to those considered in WARM include construction, consumer durables, electrical, machinery and equipment, transportation, and other industrial uses. For steel, other major uses include service centers and distributors, construction (which is modeled in WARM but discussed in the construction materials section below), transportation, and other industrial uses. Other major uses of copper include building construction, industrial machinery and equipment, transportation equipment, and consumer and general products. A mixed metals material type is also modeled in WARM, reflecting the weighted average using the latest relative recovery rates for steel and aluminum cans. See column I of Table 8 below for these recovery rates. See the "Mixed Metals" material in Table 9 below for data quality scoring that follows this weighting scheme.

Table 8. Relative Prevalence of Metals in the Waste Stream in 2015

(a) Material	(I(c) Generation (Short Tons)	(d) % of Total Container Metal Generation	(e) Recovery (Short Tons)	(f) % of Total Metals Recovery	Recovery Rate
Aluminum Cans	1,350,000	43%	670,000	35%	50%
Aluminum Ingot	NA	NA	NA	NA	NA
Steel Cans	1,740,000	57%	1,240,000	65%	71%
Copper Wire	NA	NA	NA	NA	NA

Source: EPA (2018).
NA = Not available.

The WARM emission and energy factors for these metals rely on 9 primary data sources. For the development of the aluminum can and aluminum ingot factors, the primary data sources include:

- The LCA report, *Life Cycle Impact Assessment of Aluminum Beverage Cans* (PE Americas 2010), which provides process and process non-energy data for aluminum beverage cans.[6] It is used to develop the process and process non-energy emission factors for aluminum cans and aluminum ingot and to understand the current mix of inputs (recycled vs. virgin) for WARM. This source was further disaggregated by process energy, transportation energy, and non-energy process emissions for WARM by the Aluminum Association in a spreadsheet provided to ICF and EPA (PE Americas 2011). **(KEY)**

[6] The Aluminum Association provided a detailed spreadsheet of their calculations (titled "Data for ICF-EPA_ICF formatted 08-04-11") to supplement the information published in the PE Americas report. ICF had several conversations with Senior Sustainability Specialist, Jinlong Marshall Wang to clarify the details in the calculations' spreadsheet. Because this spreadsheet is considered an extension of the PE Americas report, the calculation spreadsheet was not assessed for data quality separately from the PE Americas report (2010).

- An unpublished database with transportation energy data developed jointly by the Research Triangle Institute and EPA (RTI 2004). It documents energy consumption associated with virgin and recycled production process transportation across material types and is used to develop the transportation energy emissions factor for aluminum.

The primary data sources used to develop the steel can factors include:

- The EPA report, *Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials, Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, prepared by Franklin Associates, Ltd. (EPA 1998a). This report provides process energy, process non-energy and transportation energy data for steel cans. **(KEY)**

- Personal communication between ICF and Franklin Associates, Ltd. that culminated in a documented review of recycled content values and current mix of steel can production (identifying the percentage that is from recycled versus virgin inputs) (FAL 2003a). The communications information was based on two key resources: Ohio Department of Natural Resources "Full Circle: Buying Recycled-Content Products" fact sheet,[7] and "Municipal Solid Waste in the United States: 2000 Facts and Figures" document[8] developed by the EPA.

- Loss rate data provided by Franklin Associates, Ltd. (FAL 2003b).

The primary data sources used to develop the copper wire factors include:

- The report, *Energy and Greenhouse Gas Factors for Personal Computers,* prepared by Franklin Associates, Ltd. (FAL 2002). It presents life-cycle energy and GHG emissions for personal computers, including the GHG emissions associated with relevant copper production for use in computers. It provides the process energy, process non-energy, and transportation energy data used for the copper wire emission factors. **(KEY)**
- The report, *Flows of Selected Materials Associated with World Copper Smelting*, prepared by the U.S. Geological Survey (USGS 2004) that provides information on the percent of current production from recycled vs. virgin inputs for copper wire, and the copper wire scrap mix used to create copper ingot.

For all metals, transportation-related information was obtained from the following data sources:

- The EPA report, *Greenhouse Gas Emissions from the Management of Selected Materials* (1998b), which provides retail transportation[9] energy data used for the aluminum and steel calculations. This is the predecessor to the WARM documentation and bases its retail transportation energy on data received from Franklin Associates (FAL 1998) and the Tellus Institute (Tellus 1998) in

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[7] Ohio Department of Natural Resources. Full Circle: Buying Recycled-Content Products. www.dnr.state.oh/us/recycling/awareness/facts/buy.htm.
[8] Municipal Solid Waste in the United States: 2000 Facts and Figures. EPA530-R-02-001. Also, Franklin Associates, A Division of ERG, working papers for this report and previous versions.
[9] "Retail transportation" consists of the average truck, rail, water and other-modes transportation emissions required to get the material from the manufacturing facility to the retail/distribution point.

Background Documents A and B, respectively. The Franklin Associates Background Document A provides the aggregated process and transportation energy for eight materials, including aluminum and steel cans. The Tellus Institute Background Document B estimates the amounts and types of energy consumed in raw materials acquisition and manufacturing of eight materials, including aluminum and steel cans.

- *US Census Commodity Flow Survey Preliminary Tables, Table 1: Shipment Characteristics by Mode of Transportation for the United States* (BTS 2013). This source is a CFS on domestic freight shipments developed jointly by the BTS, the U.S. Census Bureau, and U.S. Department of Commerce. It provides data on retail transportation distance and fuel-type.

Scoring. This DQA showed that data quality is generally consistent across all metals with an average and weighted individual value of medium. Only the flow reliability and process review and completeness indicators and average value for steel cans are rated differently, with a medium-low values. While the DQA values varied across individual data sources, overall, all metals materials received an average value that corresponds with the medium data quality level. On average, the metal sources scored the best in the geographical correlation indicator category. For that indicator, the sources had medium-high data quality, conveying that the region of data correlates well to that of WARM (i.e., the United States). A summary of the results by DQI is shown in Table 9. The key findings for each of the sources used for the different metal materials are discussed below.

Table 9: **Summary of Data Quality Results for Metal Data Sources**

	DQ Values by Indicator Grouping				
Material	**Flow Reliability**	**Flow Represent-ativeness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Aluminum Cans & Aluminum Ingot	Medium	Medium	Medium	Medium	Medium
Steel Cans	Medium-low	Medium	Medium-low	Medium-low	Medium
Copper Wire	Medium	Medium	Medium	Medium	Medium
Mixed Metals	Medium	Medium	Medium	Medium	Medium
Metals	Medium	Medium	Medium	**Medium**	**Medium**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Aluminum Cans and Aluminum Ingot

The PE Americas (2010)[10] report along with the PE Americas (2011) spreadsheet had the highest data quality among the metal data sources reviewed, showing a medium-high data quality. This result is due to its strong geographical and technological correlation, flow reliability, process completeness, and process review. The PE Americas (2010) report also developed its own rating using the same general

[10] To develop the life-cycle process emission factors for aluminum, the PE Americas report uses WRI fuel emission factors, global average grid emission factors (for bauxite mining and alumina refining); North America aluminum industry mix and global aluminum industry mix (for smelting and casting) values; and the United States average grid emission factors (for secondary production, can sheet rolling, and can making). These distinct calculation inputs for the PE Americas report emission factors were sent to ICF in the “Data for ICF-EPA_ICF formatted 08-04-11” spreadsheet. Because these are inputs to the PE Americas report, the rating for the PE Americas report is reflective of these input sources as well.

scoring metric as this report (see Appendix: Data Quality Assessment Matrix). There were additional conversations with Marshall Wang of the Aluminum Association that also informed the development of the process and process non-energy emission factors, but this information was included in the supplemental spreadsheet provided to ICF and EPA (PE Americas 2011), which was assessed collectively for the purposes of the DQA.

The RTI (2004) database that is used to develop the transportation energy emissions factor for aluminum received a low data quality value. This is due to the age of the data, reducing the temporal correlation, and limited to no documentation on the other data quality indicators. Details on the development of and methodology for this database also could not be located, leading to the low data quality value.

The scoring for EPA (1998b) was based on an average of the data quality values for both the Franklin Associates and the Tellus Institute Background Documents (see Table 10 below). It received an average value of medium-high due to its high quality process completeness and geographical and technological correlation. Its data quality was lowest for temporal correlation and sample size because much of the data were uncited, and the source is over 20 years old.

Table 10: EPA 1998b Background Document Ratings

Source	Flow Reliability	Flow Representativeness	Process Review and Completeness
FAL (1998) Background Document A	Medium-High	Medium	Medium-High
Tellus (1998) Background Document B	Medium-High	Medium	High
EPA 1998b (average of background documents)	Medium-high	Medium	High

The Commodity Flow Survey (BTS 2013) has medium data quality overall. Its lowest data quality value is for process completeness, and averages as medium for its flow representativeness. EPA (2018a) has an average value of medium-low due to its high data quality across most categories, except for process review.

Steel Cans

The EPA report, *Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials* report (EPA 1998a), had high data quality for geographical correlation, technological correlation, and process completeness because its data were representative of the United States, its technology categories were equivalent, and it covered greater than 80 percent of the determined process flows. EPA (1998a) received low data quality values for temporal correlation, as the source is greater than 15 years old, and data generation and collection methods, as explanations were not found. While there were third party reviews of the EPA (1998a) document, documented reviews of the Franklin Associates data were not found, which impacted its process review data quality value.

The FAL (2003a) source, providing information on the current mix of steel can production received an average value of medium-low, with low data quality for temporal correlation. This is because it is based on data that are more than 15 years old, and low data quality for representativeness and process review and completeness as the sample size of the data is unknown, and there are no documented reviews of the data. Because the information in FAL (2003a) is based on two key resources: Ohio Department of Natural Resources "Full Circle: Buying Recycled-Content Products" fact sheet, and EPA's "Municipal Solid Waste in the United States: 2000 Facts and Figures" document, the scoring for FAL (2003a) was the average of the scoring given to those sources. The Ohio Department of Natural Resources fact sheet was not located, and thus was given a scoring of low data quality for each DQI category.

The FAL (2003b) source, providing the material loss rate information for steel cans, was not located, and therefore was given low data quality scoring across all categories. The scoring for EPA (1998b), BTS (2013), and EPA (2018a) are discussed in the aluminum can and ingot section above.

Copper Wire

FAL (2002) reflected a medium data quality value on average based on its mix of DQI values from low to high quality. It had low data quality for temporal correlation, as much of the data are more than 15 years old, and for process completeness and data collection methods due to those aspects being unknown and unable to assess. This source had medium-low data quality for flow reliability because it is an old source with data based on documented estimates rather than verified measurements of calculations. However, FAL (2002) had high data quality for geographical correlation, as the data are U.S.-based, and medium-high quality for technological correlation and process review. Because technology processes are slower to change, older data are not necessarily unrepresentative of the current production and processing landscape. However, the data quality scoring matrix takes a cautious approach by giving lower quality values to older data sources, in case the material type has a quicker technological progress timescale.

The USGS (2004) source had an average data quality level of medium. Its lowest data quality is for process completeness, and its highest data quality is for flow reliability, geographical correlation, and technological correlation.[11] The scoring for EPA (1998b) and BTS (2013) are discussed in the aluminum can and ingot section above.

Overall, the metals datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium

Recommendations

Areas for improvement include:

- Identify and incorporate data on energy consumption from a more recent and publicly published study. WARM currently pulls from the RTI (2004) database, which is over 15 years old and has the lowest data quality of all the sources. As the dataset is unpublished, there is very little information on its methodology which contributes to its low data quality.

[11] See the USGS methodology report for more information on the rating: https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/myb1-2004-surve-2.pdf

- Identify and incorporate more recent data, particularly for steel and copper wire, to replace sources such as EPA (1998a) and FAL (2002). Compared to other material categories, metal sources had the lowest data quality in the temporal correlation category, with an overall medium-low level, conveying that the data sources are on average greater than 15 years old. Because many technologies are slower to change, older data may still be relevant for many processes. However, there is still a clear need to update the data sources used in WARM for the metals section to studies based on more recent datasets.
- Update the retail transportation distance and fuel-type information with the more recently available US Census Commodity Flow Survey (from 2017).
- Assess the feasibility of updating the aluminum factors with data from a more recent assessment.[12]
- Retain documentation for all data sources, including conversations with subject matter experts. Ask subject matter experts that inform WARM to share published sources for any specific data elements.

3.3 Glass

Summary of Key Findings

Data Sources. The glass emission and energy factor calculations rely on two key data sources for process energy and process non-energy emission factors and four key data sources for the transportation emission factor calculations.

The primary data sources used for glass process energy and process non-energy data include:

- A database with process energy and process non-energy data developed jointly by the Research Triangle Institute and EPA (RTI 2004). Process energy and process non-energy data are sourced from this unpublished database that documents energy consumption associated with virgin and recycled production processes across material types. **(KEY)**
- A U.S. Department of Energy (DOE) report, *Energy and Environmental Profile of the U.S. Glass Industry*. DOE (2002), which provides assumptions on the average composition of glass and fuel used to combust glass. This source provides an energy and environmental profile of the U.S. glass industry.
- In-house data from Franklin Associates (FAL 2003b) provides information on the current mix of production from virgin and recycled inputs for glass manufacturing, typical glass recycled content values in the marketplace, and glass loss rates.

The primary data sources used for the transportation emission calculations include:

[12] Wang 2022. "The Environmental Footprint of Semi-Fabricated Aluminum Products in North America." The Aluminum Association. January 2022. https://www.aluminum.org/sites/default/files/2022-01/2022_Semi-Fab_LCA_Report.pdf (Accessed: January 17, 2023).

- *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (FAL 1994). This report is a study on the role of recycling in integrated solid waste management published by Franklin Associates. This report provides GHG emissions from transportation energy usage for transportation of waste to the combustion facility.

- *US Census Commodity Flow Survey Preliminary Tables, Table 1: Shipment Characteristics by Mode of Transportation for the United States* (BTS 2013). This source is a Commodity Flow Survey (CFS) on domestic freight shipments developed jointly by the Bureau of Transportation Services (BTS), the U.S. Census Bureau, and U.S. Department of Commerce. It provides additional assumptions on *retail* transportation energy usage (average shipping distances and modes) for glass.

- Typical transportation fuel efficiencies are sourced from the EPA report, *Greenhouse Gas Emissions from the Management of Selected Materials*, prepared by ICF for EPA, (EPA 1998b), which is the original WARM emission factor methodology document.

Scoring. On average, the data quality for the glass data sources is highest within the geographical and technological correlation indicators. On average, the sources reflect medium data quality, conveying that the region of data correlates relatively well to that of WARM (the United States) and the majority of technology categories are equivalent.[13] The low data quality of the key source for the glass analysis brought down the weighted average value to medium-low. A summary of the results by data quality indicator groupings is shown in Table 11. The key findings for each of these sources are discussed below.

Table 11: Summary of Data Quality Results for Glass Data Sources

	DQ Values by Indicator Grouping				
Material	**Flow Reliability**	**Flow Representative-ness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Glass	Medium	Medium	Medium	**Medium**	**Medium-low**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

RTI (2004) was considered to be a low quality source as it is an unpublished database developed by the Research Triangle Institute and EPA; and details on the development of and methodology for that database have not been found. This is especially salient as the process energy and non-process energy emission factors for glass is almost entirely based on RTI (2004), with additional glass composition assumptions sourced from DOE (2002). The highest data quality was with FAL (1994), which includes a fairly robust dataset; however, the data collection occurred in 1992.

FAL (2003a) is based on in-house data provided by Franklin Associates to ICF. This source was not found as it is based on in-house data from Franklin Associates, and therefore was considered to reflect low data quality across all categories.

[13] Technology categories are process design, operating conditions, material quality, and process scale.

For the development of the weighted average glass data quality value, the RTI (2004) data source is weighted more heavily than the rest of the sources as it is the main source of process energy and process non-energy data used for the development of WARM glass emission and energy factors.

Overall, the glass datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium-low

The difference between the medium quality average indicator value and the medium-low quality average weighted indicator value shows the impact of a key data source being low quality. RTI (2004) was determined to be a low quality, out of date source with a poorly documented methodology. However, WARM relies on RTI (2004) as a key source to inform glass emissions, which brings down the overall quality of the glass section, particularly when considering an average that weighs RTI (2004) more heavily than other sources.

Recommendations

Areas for improvement include:

- Conduct research to identify a more recent peer-reviewed study for the glass process energy emission factors than the current data source, RTI (2004). On average, the data quality for the glass data sources is lowest within the temporal correlation category.
- Identify more recent and publicly available information on the current mix of production for glass.
- Update the retail transportation distance and fuel-type information with the more recently available US Census Commodity Flow Survey (from 2017).
- Consider a more updated source for transportation fuel efficiencies (such as fuel efficiencies published by NREL[14]).

3.4 Paper

Summary of Key Findings

Data Sources. Paper materials and products included in WARM are magazines, newspaper, office paper, phonebooks, textbooks, and corrugated containers such as cardboard packing boxes. The paper material emission factor and energy factor calculations rely on seven data sources. Of these, three key data sources informed process energy, process non-energy, and transportation emission factors, and therefore were weighted more heavily when determining overall data quality of paper sources. These include:

- An unpublished database developed jointly by the Research Triangle Institute and the U.S. Environmental Protection Agency Office of Research and Development (RTI 2004), which provides information on the industrial process emissions and energy mix of paper materials including corrugated containers, magazines, newspaper, office paper, phonebooks, and textbooks. **(KEY)**

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[14] Alternative Fuels Data Center: Maps and Data - Average Fuel Economy by Major Vehicle Category (energy.gov)

- The EPA Report, *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, *Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials*, prepared by Franklin Associates, Ltd. (EPA 1998a), which provides information on energy requirements for production of recycled corrugated containers. **(KEY)**

- *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, Background Document A, Attachment 1: A Partial Life Cycle Inventory of Process and Transportation Energy for Boxboard and Paper Towels, published by Franklin Associates, Ltd. (FAL 1998), which provides information on the composition of mixed paper and energy requirements for production of virgin and recycled boxboard. **(KEY)**

The paper factors also relied on other non-key data sources:

- Personal communication between ICF and Franklin Associates, Ltd. that culminated in a documented review of recycled content values and current mix of paper material production (identifying the percentage that is from recycled versus virgin inputs) (FAL 2003a).

- In-house data from Franklin Associates (FAL 2003b) provides information on retention rates during recycling of paper materials.

- *U.S. Census Commodity Flow Survey Preliminary Tables*, published by the U.S. Bureau of Transportation Statistics (BTS) Research and Innovative Technology Administration (BTS 2013), which provides data on transportation energy.

- Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013, a report published by the U.S. EPA (EPA 2015), which provides measurements on fuel-specific carbon content and coefficients.

Scoring. A summary of the results by data quality indicator groupings is shown in Table 12. The key findings for each of these sources are discussed below.

Table 12: Summary of Data Quality Results for Paper Data Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	**Flow Represent-ativeness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Paper	Medium-low	Medium	Medium-low	**Medium-Low**	**Medium**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Key sources for paper, RTI (2004), EPA (1998a), and FAL (1998), provide process energy, process non-energy, and transportation energy requirements for the manufacturing of various paper materials. Overall, the paper flow representativeness indicator reflected medium data quality, while the flow reliability and process review and completeness indicators reflected medium-low data quality. On average, the paper data sources were of low quality for temporal correlation; medium-low for flow reliability, data collection methods, and process review; and medium quality for geographical correlation, technological correlation, and process completeness. Poor temporal correlation was due to the publication years of the paper data sources, which range from 1998 to 2015. Data collection methods saw more variable data quality, but two sources, including key source RTI (2004) and EPA (1998a), were deemed low quality for this category as the sources did not list sites or time periods sampled. This left representativeness unknown and indicated a poor data source. Concerning geographical correlation, the data sources for paper were created using data from the United States, which is the same region of data that WARM represents. On average, indicators were determined to be of medium-low quality, and of medium quality for the weighted average giving additional weight to the key data sources.

RTI (2004) had the lowest data quality among the key paper sources. As noted previously, RTI (2004) is an unpublished database developed by the Research Triangle Institute and EPA. Details on the methodology of this database are not available, resulting in an overall low-quality level. EPA (1998a) had high data quality for geographical correlation, technological correlation, and process completeness because its data were representative of the United States, its technology categories were equivalent, and it covered greater than 80 percent of the determined process flows. EPA (1998a) received low data quality values for temporal correlation, as the source is greater than 15 years old, and data generation and collection methods, as explanations were not found. While there were third party reviews of the EPA (1998a) document, documented reviews of the Franklin Associates data were not found, which impacted its process review data quality value. FAL (1998) had medium-high to high data quality for five of the seven indicators. Temporal correlation, due to age of data, was the lowest mark for this source.

One of the other sources, EPA (2015), which provides corrugated containers' fuel-specific carbon content, was a high data quality source, as it is a more recent report published by the EPA and verified by multiple third parties. This report also has Annexes that detail methodology, scale, scope, and sources that reflect a higher quality source.

Overall, the paper datasets scored as follows:

- **Average indicator:** Medium-low
- **Average weighted indicator:** Medium

Recommendations

Areas for improvement include:

- Update all paper data sources to more recent sources where applicable, based on the quality of the temporal correlation (low data quality). Some sources may not have more recent versions, but updated data should be used if possible. This dataset is most in need of updating.
- Update all paper data sources from those that use data generated from estimates to data generated from verified or non-verified measurements or calculations, which would improve the data sources' flow reliability, and therefore the reliability of WARM.
- Identify more recent and reliable source(s) to update the RTI (2004) data set providing manufacturing and transportation energy use data for all paper types (corrugated containers, magazines/third-class mail, newspaper, office paper, phonebooks, and textbooks).

3.5 Electronics

Summary of Key Findings

Data Sources. Electronics covered in WARM include desktop CPUs, portable electronic devices (tablets, laptops, and smartphones), flat-panel displays (TVs and monitors), CRT displays, electronic peripherals (mice and keyboards), and hard-copy devices (i.e., printers), and a mixed electronics category, which is a combination of the other electronic categories weighted by their prevalence in the U.S. waste stream. The electronics material emission factors and energy factor calculations rely on 16 data sources for information regarding process emissions of electronic components, the component mass share within WARM's electronic categories, recovery and recycling practices for the different electronics, and the prevalence of electronic types in the U.S. waste stream.

Four data sources played a key role in developing the final WARM electronic emission and energy factors:

- Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) 2 Model (ANL 2018), which is used to source process emissions for many of the electronic materials' components, including plastics and some metals. **(KEY)**

- Ecoinvent Centre's life cycle dataset v3.2 (Ecoinvent Centre 2015), which was used to source process emissions for additional components and metal types, including gold, silver, and silica sand. **(KEY)**

- The report, *Sustainable Materials Management for the Evolving Consumer Technology Ecosystem* (Babbitt et al. 2017), which calculates the component mass share in the electronic types in WARM. These percentages combined with the process emissions of the component types formed the basis for the component share of various metals, plastics, and other rare metals found in each of WARM's electronic categories. **(KEY)**

- Journal article, *Comparing embodied greenhouse gas emissions of modern computing and electronics products* (Teehan and Kandlikar 2013), which includes virgin production energy data for printed circuit boards, flat panel display modules, and batteries. **(KEY)**

Process emissions for the various components come largely from the ANL 2018's GREET model, Ecoinvent v3.2, and Teehan and Kandlikar 2013.[15] Multiplying component mass shares from Babbitt et al. (2017) by these process emissions yielded a majority of the overall emissions for electronic types in WARM.

[15] Teehan and Kandlikar 2013 data verification methodology involved the hand disassembly of printed circuit boards, flat panel display modules, and batteries to verify the mass share of different components. These masses were then entered into the Ecoinvent Database to gather emission results, albeit an earlier version than the one cited by WARM (v2.2 versus v3.2).

Additional sources are used to help fill in the gaps of information regarding specific emission factors for electronic types and component mass share in WARM, background information in the supporting documentation, and ancillary data needed to form accurate assumptions in WARM. These include:

- End-of-life management practices and emissions from recycling are sourced mainly from Bigum et al. (2012) and Vanegas et al. (2017). Additional information is sourced from Dewulf et al. (2010) for information on battery recycling and Turner et al. (2015) on CRT recycling practices.
- *The Electronics Recycling Landscape* report (Mars et al. 2016), which provides information on the shares of electronic types in the U.S. waste stream used in the mixed electronics category in WARM.
- The assumption for share of electronic types in the U.S. waste stream used in the mixed electronics material type is sourced from Mars et al. (2016).
- A report on cellphone materials and life cycle emissions of its components (Andrea and Vaija 2014).
- Four reports conducted by Franklin Associates, studying the life cycle emissions of plastic (FAL 2011a, FAL 2011b, FAL 2018) and copper (FAL 2002), including the production phase and recycling.
- Journal article, *Improving Resource Efficiency through Recycling Modelling: A Case Study for LCD TVs* report (Vanegas et al. 2015) that studies process emission information on LCD TVs.
- The report, *Life Cycle Assessment of a Personal Computer* (Hikwama 2005), that studies the mass share in a personal computer.

Recycling and end-of-life information was sourced from the following sources:

- Journal article, *Metal recovery from high-grade WEEE: A life cycle assessment* (Bigum et al. 2012), which reviews recycling emissions for electronic types, namely rare metals in circuit boards.
- A report on the process and associated emissions from recycling lithium cobalt oxide batteries (Dewulf et al. 2010).
- EPA's 2008 report *Electronics Waste Management in the United States: Approach I*, which provided additional information on electronic disposal practices, used mainly in the supporting documentation chapter.
- A report on CRT material recovery and recycling practices (Turner et al. 2015).

Scoring. Data quality for electronics data sources ranged from medium to high. The variation among sources is due largely to differences in data collection methods (measurements versus documented calculations), review process of the studies, and the age of the sources. A summary of the electronics results by data quality indicator groupings is shown in Table 13. The key findings for each of these sources are discussed below. Unlike other material categories in WARM, most sources cited in the electronics category are used by many or all material types. This is primarily because these sources studied the emission factors from component materials (e.g., copper, plastic, aluminum) found in most or all of the electronic materials. Final emission values for electronic materials were then calculated using the proportion of the component materials used in each material. For this reason, the sources were grouped together under a single "Electronics" category.

Table 13: Summary of Data Quality Results for Electronic Sources

	DQ Values by Indicator Grouping				
Material	**Flow Reliability**	**Flow Represent-ativeness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Electronics	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Overall, flow reliability and process completeness reflect the highest data quality of the indicators across the data sources, as the sources covered all aspects of the life-cycle flow and generated data in a precise and repeatable manner.

Other key findings from the review include:

- The estimated mean year of publication across the electronics sources was 2013, which reflects a temporal data quality level of medium.
- The largest amount of variance in an indicator category came from the data collection methods indicator, which focuses on "the robustness of the sampling methods" used by the study. Those studies that sourced data from products and surveys across numerous companies in the industry were considered as high quality, while those that examined only a handful of products received data quality levels of medium-low and low.
- Two of the most critical sources – ANL (2018), Babbitt et al. (2017) – had high data quality, and the third most critical s–rce -- Ecoinvent Centre (2015) – had medium-high data quality. This was due in large part to their high-quality data generation methods, diligent review process, and recency of publishing.
- Rather than attempt to gather data by electronic type, the current approach used in WARM examines studies that provide emission estimates on the components that make up these electronics and then combines that with Babbitt et al. 2017's findings on mass shares to calculate overall life cycle emissions.

Overall, the electronics datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Recommendations

Areas for improvement include:

- Corroborate Babbitt et al. (2017) findings with another, recent source that similarly examines the overall material share of different components in electronic types.
- Identify alternative higher quality data sources to potentially update the sources that received a data quality value of medium or lower on their overall assessment, including Vanegas et al. (2017),[16] FAL (2002), Dewulf et al. (2010), Hikwama (2005), and Mars et al. (2016).
- Update process emissions from the latest versions of the GREET model (2018 versus 2022) and Ecoinvent (v3.2 versus v3.9).

3.6 Construction Materials

Summary of Key Findings

Data Sources. Construction materials included in WARM include asphalt concrete, asphalt shingles, carpet, clay bricks, concrete, dimensional lumber, drywall, fiberglass insulation, fly ash, medium-density fiberboard, structural steel, vinyl flooring, and wood flooring. The data quality analysis for construction materials relied on a total of 52 data sources. Of these, the majority of process energy, process non-energy, and transportation emission factors data related to construction materials relies on 21 key data sources, which were weighted more heavily when assessing data quality due to their importance in WARM calculations:

- Asphalt Concrete
    - *Life-Cycle Assessment of Warm-Mix Asphalt: An Environmental and Economic Perspective* is a life cycle assessment presentation for Louisiana State University (Hasan 2009), which provides information on the composition of hot-mix asphalt. **(KEY)**
    - *Road Rehabilitation Energy Reduction Guide for Canadian Road Builders,* a guide published by the Canadian Industry Program for Energy Conservation (Canadian Industry Program for Energy Conservation 2005), which provides data on the energy consumption of manufacturing asphalt. **(KEY)**
- Asphalt Shingles
    - *Life Cycle Analysis of Residential Roofing Products* (Athena Sustainable Materials Institute 2000) is a life cycle report that provides information on the manufacturing of virgin asphalt shingles. **(KEY)**
    - *Environmental Issues Associated with Asphalt Shingle Recycling,* a report prepared for Construction Materials Recycling Association (CMRA) and the U.S. EPA (CMRA 2007), which provides data on the composition, recycling, and combustion of shingles. **(KEY)**
- Carpet
    - *Energy and Greenhouse Gas Factors for Personal Computers* (FAL 2002) is a report that provides data on certain material components that are used to make carpet. This source sheds light on the fuel mix and energy use in the manufacturing of components used in the production of carpet. **(KEY)**
    - *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Carpet and Personal Computers* (EPA 2003a) is a report that provides data on the process emissions and fuel mix in carpet production. **(KEY)**

[16] Vanegas et al. 2017's score suffers due to poor scores in the data collection methods, flow reliability, geographical correlation, and temporal correlation indicators.

- Clay Bricks
    - *Life Cycle Analysis of Brick and Mortar Products* (Athena Sustainable Materials Institute 1998) is a life cycle report that provides data on the process and transportation emissions of clay bricks. **(KEY)**
    - *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2016* (EPA 2018b) is a report that provides measurements and data on the life cycle emissions factors related to manufacturing and transportation of clay bricks. **(KEY)**
- Concrete
    - *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Clay Brick Reuse and Concrete Recycling* (EPA 2003b) is a report that documents the process and transportation emissions of the life cycle of virgin concrete. **(KEY)**
- Dimensional Lumber
    - *Life-cycle energy and GHG emissions for new and recovered softwood framing lumber and hardwood flooring considering end-of-life scenarios* (Bergman et al. 2013) is a report that provides cradle to gate greenhouse gas emissions data for new and recycled dimensional lumber. **(KEY)**
- Drywall
    - *Life Cycle Analysis of Gypsum Board and Associated Finishing Products,* published by Athena Sustainable Materials Institute (Venta 1997), which provides data on the manufacturing, fuel mix, and transportation emissions associated with the life cycle of drywall. **(KEY)**
    - *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Two Polyurethane Precursors,* prepared for the Plastics Division of the American Chemistry Council (FAL 2007), which provides data on the process emissions and fuel mix associated with producing chemicals and materials used in the manufacturing of drywall. **(KEY)**
- Fiberglass Insulation
    - *Building for Environmental and Economic Sustainability (BEES) Technical Manual and User Guide* (Lippiatt 2007) is a guide to BEES, a software that helps users select environmentally preferred, cost-effective building products. The user guide summarizes data found in BEES, including the manufacturing and process emissions of fiberglass insulation. **(KEY)**
- Fly Ash
    - *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Fly Ash Used as a Cement Replacement in Concrete* (EPA 2003c) is a life cycle analysis that provides data on the recycling emissions of fly ash. **(KEY)**
- Medium-Density Fiberboard
    - *Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon,* published in Wood and Fiber Science (Wilson 2010), which provides information on the life cycle manufacturing and transportation emissions of medium-density fiberboard. **(KEY)**
- Structural Steel
    - *Structural Section and Hot-Dip Galvanized Steel Production in China – Life cycle assessment report* (American Iron and Steel Institute [AISI] 2017) is an industry report that provides information on the manufacturing and transportation life cycle emissions associated with virgin inputs of structural steel. **(KEY)**

- Fabricated Structural Steel – Environmental product declaration supporting background report (AISI 2016) is an industry report describing the process emissions and manufacturing inputs of recycled structural steel. **(KEY)**

- Vinyl Flooring
    - *Life Cycle Assessment of PVC and of principal competing materials,* commissioned by the European Commission (Baitz et al. 2004), which provides data on the life cycle of polyvinyl chloride (PVC) and its use in the composition of vinyl flooring. **(KEY)**
- Wood Flooring
    - *Environmental Impact of Producing Hardwood Lumber Using Life-Cycle Inventory*, published in Wood and Fiber Science (Bergman and Bowe 2008), is a life cycle report that provides information on the manufacturing material consumption of wood flooring. **(KEY)**
    - *Life-Cycle Inventory of Solid Strip Hardwood Flooring in the Eastern United States,* a graduate student report published at the University of Wisconsin — Madison (Hubbard and Bowe 2008), provides data on the manufacturing and transportation emissions associated with the life cycle of wood flooring. **(KEY)**
    - *Life Cycle Analysis of Residential Roofing Products* (Athena Sustainable Materials Institute 2000) is a life cycle report that provides information on the manufacturing of virgin wood products, which are also used in wood flooring.[17] **(KEY)**

Other data sources for specific construction materials include:

- Asphalt Concrete
    - *A Life Cycle Inventory for Road and Roofing Asphalt* is a life cycle analysis report prepared for Athena Sustainable Materials Institute (Athena Sustainable Materials Institute 2001), which provides information on process emission factors of asphalt concrete.
    - *1997 Economic Census, Mining* (U.S. Census Bureau 1997) is a government report on the U.S. mining industry that provides data on material and fuel mix inputs for asphalt concrete.
    - *A Life-Cycle Analysis of Alternatives for the Management of Waste Hot-Mix Asphalt, Commercial Food Waste, and Construction and Demolition Waste* is a master's in civil engineering thesis published in the North Carolina State University library (Levis 2008), which provides information on recycling emissions of asphalt concrete.
    - *U.S. Life-Cycle Inventory Database,* a comprehensive report published by the National Renewable Energy Laboratory (NREL 2009), which provides information on the energy use of producing limestone that is used to manufacture asphalt concrete.
- Asphalt Shingles
    - *Construction and Demolition Debris Recycling: Methods, Markets, and Policy* is a master's thesis for the University of Central Florida (Cochran 2006), which provides data on recycling emissions for asphalt shingles.
    - *Materials Recycling and Processing in the United States, Fifth Edition* is a directory of data (Berenyi 2007), which provides recycling loss rates of asphalt shingles.

[17] Athena Sustainable Materials Institute (2000) is a key source for two Construction Materials, Wood Flooring and Asphalt Shingles.

- Carpet
    - *Eco-profiles of the Plastics Industry—Polyamide (Nylon 6)* (Plastics Europe 2005a) is a material profile that informs the process and transportation emissions of chemicals used to produce carpet.
    - *Eco-profiles of the Plastics Industry—Polyamide (Nylon 66)* (Plastics Europe 2005b) is a material profile that informs the process and transportation emissions of chemicals used to produce carpet.
- Concrete
    - *Aggregates from Natural and Recycled Sources–Economic Assessments for Construction Applications* (Wilburn and Goonan 1998) is a report that informs the process and transportation emissions of recycled concrete.
- Dimensional Lumber
    - *Environmental Product Declaration* (American Wood Council 2013) is a material report that provides cradle to gate greenhouse gas emissions data for new dimensional lumber.
- Drywall
    - *Composition of Municipal Solid Waste in the United States and Implications for Carbon Sequestration and Methane Yield* (Staley and Barlaz 2009) is a report that informs the moisture content and carbon storage factor of drywall.
    - *Comprehensive life-cycle analysis of RAP: Comprehensive life-cycle analysis of plasterboard* (WRAP 2008) is a life cycle analysis report that informs the composition of recycled drywall and energy requirements for drywall recycling.
    - *US Census Commodity Flow Survey Preliminary Tables*, published by the U.S. Bureau of Transportation Statistics (BTS) Research and Innovative Technology Administration (BTS 2013), which provides data on transportation energy.
    - *2002 Commodity Flow Survey* (U.S. Census Bureau 2004) is a report that measures the transportation energy associated with recycled drywall.
- Fiberglass Insulation
    - *Life Cycle Analysis of Residential Roofing Products* (Athena Sustainable Materials Institute 2000) is a life cycle report that provides information on the manufacturing of virgin fiberglass insulation, specifically that used in roofing.
    - *US Census Commodity Flow Survey Preliminary Tables*, published by the U.S. Bureau of Transportation Statistics (BTS) Research and Innovative Technology Administration (BTS 2013), which provides data on transportation energy.
    - *Glass Recycling–Life Cycle Carbon Dioxide Emissions*, prepared for the British Glass Manufacturers Confederation – Public Affairs Committee (Enviros Consulting 2003), is a life cycle report that provides information on glass recycling and transportation emissions.
    - *U.S. Life-Cycle Inventory Database,* a comprehensive report published by the National Renewable Energy Laboratory (NREL 2009), which provides information on the sourcing of soda ash and limestone that are inputs in the manufacturing of fiberglass insulation.
- Medium-density Fiberboard
    - Environmental Product Declaration (Composite Panel Association 2018) is a cradle-to-gate life cycle report that provides information on the manufacturing emissions, virgin inputs, and overall medium-density fiberboard production.

- Structural Steel
    - *US Census Commodity Flow Survey Preliminary Tables*, published by the U.S. Bureau of Transportation Statistics (BTS) Research and Innovative Technology Administration (BTS 2013), which provides data on transportation energy.
    - *Greenhouse Gas Emissions from the Management of Selected Materials,* published by the U.S. EPA (EPA 1998b), which provides information on retail transportation energy use. *Global Steel Trade Monitor* (U.S. Department of Commerce 2020) is a government economic report that provides information on the virgin inputs that compose structural steel.
    - *2020 World Steel Figures* (World Steel Association 2020) is an annual global industry report that provides data on the virgin inputs that compose structural steel.
- Vinyl Flooring
    - *Resilient Flooring: A Comparison of Vinyl, Linoleum and Cork*, published by the Georgia Tech Research Institute (Jones 1999), which provides data on the manufacturing process and emissions of vinyl flooring.
    - *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Two Polyurethane Precursors,* prepared for the Plastics Division of the American Chemistry Council (FAL 2007), which provides data on the manufacturing emissions associated with producing chemicals and materials used in the production of vinyl flooring.
    - *Eco-profile of high volume commodity phthalate esters (DEHP/DINP/DIDP)*, a report prepared for The European Council for Plasticisers and Intermediates (ECPI) (ECOBILAN 2001), which provides data on the environmental impact of chemicals used in the production of vinyl flooring, as well as information on transportation emissions.
    - *US Census Commodity Flow Survey Preliminary Tables*, published by the U.S. Bureau of Transportation Statistics (BTS) Research and Innovative Technology Administration (BTS 2013), which provides data on transportation energy.
- Wood Flooring
    - *Life-cycle energy and GHG emissions for new and recovered softwood framing lumber and hardwood flooring considering end-of-life scenarios*, published in Wood and Fiber Science (Bergman et al. 2013), which provides data on the material consumption associated with manufacturing wood flooring.
    - *Environmental Product Declaration* (American Wood Council 2013) is a material report that provides cradle to gate greenhouse gas emissions data on virgin manufacturing inputs for wood flooring.
    - *US Census Commodity Flow Survey Preliminary Tables*, published by the U.S. Bureau of Transportation Statistics (BTS) Research and Innovative Technology Administration (BTS 2013), which provides data on transportation energy.

Two data sources could not be located and thereby were deemed low quality by default:

- Carpet
    - *Personal communication with Matthew Realff, Associate Professor of Chemical and Biomolecular Engineering* (Realff 2011), which provides information on material composition and recycling of carpet.
- Fiberglass Insulation
    - *Email communication with Scott Miller, Knauf Insulation, and Beth Moore* (Miller 2010), which provides information on recycling emission of fiberglass insulation.

Scoring. Data source analysis was conducted by material, and then averaged to show that, overall, sources for construction materials were of medium-high data quality. A summary of the results by data quality indicator groupings is shown in Table 14. The key findings for each of these sources used for the different construction materials are discussed below and details on the individual sources' scores can be found in the Appendix.

Table 14: Summary of Data Quality Results for Construction Materials Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	Flow Represent-ativeness	Process Review and Completeness	Average	Weighted Average
Asphalt Concrete	Medium-high	Medium	Medium-high	**Medium-high**	**Medium**
Asphalt Shingles	Medium-low	Medium	Medium	**Medium**	**Medium**
Carpet	Medium	Medium-low	Medium-low	**Medium-low**	**Medium**
Clay Bricks	Medium-high	Medium-high	High	**Medium-high**	**High**
Concrete	High	Medium-high	Medium	**Medium-high**	**Medium-high**
Dimensional Lumber	Medium-high	Medium-high	High	**Medium-high**	**Medium-high**
Drywall	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Fiberglass Insulation	Medium	Medium	Medium	**Medium**	**Medium**
Fly Ash	Medium-high	Medium-high	Medium	**Medium-high**	**Medium-high**
Medium-density Fiberboard	Medium-high	Medium-high	High	**Medium-high**	**Medium-high**
Structural Steel	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Vinyl Flooring	Medium-high	Medium	Medium-high	**Medium**	**Medium**
Wood Flooring	Medium-high	Medium	Medium-high	**Medium-high**	**Medium-high**
Construction Materials	**Medium-high**	**Medium-high**	**Medium-high**	**Medium-high**	**Medium-high**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Asphalt Concrete

Asphalt concrete emissions factors and energy factors rely heavily on the data sourced from Hassan (2009) and Canadian Industry Program for Energy Conservation (2005). They also use information from the US Census Bureau (1997), Athena Sustainability Materials Institute (2001), Levis (2008), and NREL (2009).

Hassan (2009) is a life cycle analysis of warm-mix asphalt, and provides information on emissions factors and the composition of asphalt concrete. Despite being an older source with little information about the sample size or reviewer process, Hassan (2009) was deemed to have, on average, medium quality data as it was from the same area of study as WARM, and all technology categories were equivalent (e.g., process design, operating conditions, material quality, and process scale).

Of the asphalt concrete sources, US Census Bureau (1997), Levis (2008), and Athena Sustainability Materials Institute (2001) were deemed to have the highest quality data, and received overall medium-high data quality values. US Census Bureau (1997) provided data on material and fuel mix inputs, Levis

(2008) informed recycling emissions, and Athena Sustainability Materials Institute (2001) included data on process emissions factors. All other sources for asphalt concrete had a medium data quality value.

On average, asphalt concrete had medium-high quality sources for its process review and completeness indicators. This indicates that the sources for this material tended to be reviewed by third parties to verify data and covered a high percentage of process flows for this material.

The asphalt concrete datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium

Asphalt Shingles

Asphalt shingles emissions factors and energy factors rely on two key sources: CMRA (2007) and Athena Sustainable Materials Institute (2000). Other non-key sources include Cochran (2006) and Berenyi (2007).

CRMA (2007) provides information on the emissions and energy factors of the composition, recycling, and combustion of asphalt shingles. This source has a medium-low data quality, as it has low data quality values for temporal correlation, process indicators, and data collection methods. However, the source did have high geographical correlation as it is focused on the United States.

Athena Sustainable Materials Institute (2000) is the source for virgin production and manufacturing for residential roofing materials, including asphalt shingles. This source was deemed medium-high quality, as it reflected high data quality for technological correlation, data collection methods, and process completeness data quality indicators, but reflected low-quality data for temporal correlation and medium quality data for geographical correlation as it is a Canadian study conducted over 15 years ago.

The asphalt shingles datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium

Carpet

Carpet emissions factors and energy factors rely on data from FAL (2002) and EPA (2003a). Other sources also contribute: Plastics Europe (2005a) and Plastics Europe (2005b). Realff (2011) was not located and was therefore deemed low quality.

FAL (2002) is a report on the fuel mix and energy use in the manufacturing of personal computers that contains fuel and energy use information relevant to material components used to manufacture carpet. The data quality of this source is medium based on its mix of DQI values from low to high quality. It had low data quality for temporal correlation, as much of the data are more than 15 years old, and for process completeness and data collection methods due to those aspects being unknown and unable to assess. This source had medium-low data quality for flow reliability because it is an old source with data based on documented estimates rather than verified measurements of calculations. However, FAL

(2002) had high data quality for geographical correlation, as the data are U.S.-based, and medium-high quality for technological correlation and process review.

EPA (2003a) is a report on the life cycle of carpet and personal computers that provided insight on fuel mix and process emissions. The source had medium-high data quality. While this is an old source, it had high ratings for geographical correlation, technological correlation, data collection methods, and process completeness, as this is a U.S.-located report with verified data based on measurements that cover a large percentage of flows, representative sample size, and a variety of technology types.

The carpet datasets scored as follows:

- **Average indicator:** Medium-low
- **Average weighted indicator:** Medium

Clay Bricks

WARM emissions factors and energy factors for clay bricks rely on two sources, both of which are key sources: Athena Sustainable Materials Institute (1998) and EPA (2018b). Both provide key information on the process and transportation emissions of clay bricks. Athena Sustainable Materials Institute (1998) had medium-high data quality overall due to high and medium-high scores for flow and process indicators as the data was based on calculations, used a representative sample size, had third party reviewers, and a high percent of life cycle flows were covered. However, the source had low data quality for temporal and geographical correlation for being an old life cycle analysis based in Canada. EPA (2018b) is a high-quality source as it is more recent, based in the United States, and has other high quality flow indicators and process indicators due to a large sample size representative of the clay bricks industry, the use of third-party reviewers, and a large breadth of life cycle flows covered by the report.

The clay bricks datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** High

Concrete

Concrete emissions, energy, and transportation factors rely on two sources: EPA (2003b) and Wilburn and Goonan (1998). EPA (2003b) is a medium-high quality key source that provides information into process and transportation emissions for virgin concrete. This source had low quality for temporal correlation, as it is over 15 years old, and medium-low quality for process review, as there was internal review but not a documented third-party review of the study. All other process and flow indicators were deemed high or medium-high quality as the sources covered over 80 percent of recycled and virgin concrete life cycle flows and considered a representative sample size in the United States. Wilburn and Goonan (1998) was also a medium-high quality source. This source provided information on process and transportation emissions for recycled concrete, and had similar scores to EPA (2003), where its lowest data quality indicators were temporal correlation and internal review, and all others were high to medium quality.

The concrete datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Dimensional Lumber

Dimensional lumber relies on Bergman et al. (2013) and American Wood Council (2013). Both sources provide data related to the life cycle emissions of dimensional lumber. Bergman et al. (2013) considers the cradle to grave emissions of new and recycled dimensional lumber, while American Wood Council (2013) is a report on the cradle-to-grave emissions of new dimensional lumber. Both sources had medium-high quality flow reliability as they use verified data based on calculations and medium-low quality temporal correlation as they are over 10 years old. They also had medium-high or high quality data quality values for all other flow and process indicators, due to geographical correlation being based in America or North America, a highly representative sample size for data collection, documented third party reviewers, and a high percentage of flows covered.

The dimensional lumber datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Drywall

Drywall relies on six sources to inform energy factors and emission factors: Venta (1997), FAL (2007), WRAP (2008), BTS (2013), Staley and Barlaz (2009), and US Census Bureau (2004). Of these sources, Venta (1997) and FAL (2007) play a greater role in informing the energy and emissions factors of drywall. Venta (1997) provides data on manufacturing emissions and fuel input, as well as transportation emissions for the life cycle of drywall. FAL (2007) gives insight into process emissions and energy use of drywall from when it is produced to when it hits the market. Both were deemed medium-high quality, as both sources had high data quality values for technological correlation, data collection methods, process review, and process completeness. They used an equivalent variety of technology types, a representative sample size, verified third party reviewers, and data from more than 80 percent of the drywall market over an adequate period. While they have a similar data quality, Venta (1997) had lower data quality than FAL (2007) as it is a much older source and is based in Canada instead of the United States.

US Census Bureau (2004) is a commodity survey that informed transportation energy factor for recycled drywall. For this source, which overall reflected medium-high data quality, each flow and process indicator provided high quality data besides temporal correlation, which was low quality as the source is over 15 years old. WRAP (2008) provides the composition of recycled drywall and energy requirements for drywall recycling that informed process emissions. This source was a medium quality source as it was an older summary of a study conducted in the United Kingdom. It had low quality for process review and medium-low quality for temporal and geographic correlation, but medium to high quality for other process and flow indicators. BTS (2013) was also medium quality, as it has a low-quality process completeness due to an unknown percentage of flows evaluated, and medium-low quality for temporal correlation and process review. Staley and Barlaz (2009) is a report that compares 11 statewide waste characterization studies to understand the overall composition of discarded waste in the United States and how that impacts carbon sequestration. This source was deemed to be of medium-high data quality, as it calculates data from a wide range of facilities in states across every region of the United States. The report considers a variety of technology categories, includes operating conditions and material quality, and covers the majority of process flows. Despite these high quality data indicators, the source reflected medium-high quality due to low-quality temporal correlation, as the source is from 2009.

The drywall datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Fiberglass Insulation

One source, Lippiatt (2007), plays a key role in understanding the life cycle energy factors and emission factors of fiberglass insulation. Other sources include: Athena Sustainable Materials Institute (2000), Enviros Consulting (2003), NREL (2009), Miller (2010), and BTS (2013). Athena Sustainable Materials Institute (2000) and BTS (2013) are cross cutting sources, as the former is also used to inform the life cycle factors of asphalt shingles, and the latter is also used to inform the life cycle of drywall. The Miller (2010) data source was unable to be located to determine data quality, so it was deemed low quality.

Lippiatt (2007) provides information on the manufacturing process and related emissions for fiberglass insulation. This source is a report based on a tool that measures the environmental performance and life cycle emissions of various building materials, including fiberglass insulation. This was determined to be a medium-high quality source, as it had high data quality ratings for most flow indicators and process indicators. However, this source is over 15 years old and based on verified calculations rather than verified measurements resulting in low quality temporal correlation and flow reliability, respectively.

Enviros Consulting (2003) covers glass recycling and transportation emissions for fiberglass insulation. This medium quality source is a life cycle assessment conducted in the United Kingdom over 15 years ago, lowering its geographic and temporal correlations. The source also had a medium-low quality process review, as the review was conducted by an internal reviewer. The remaining indicators, technological correlation, data collection methods, process review and completeness, and flow reliability were deemed high or medium-high quality. This is due to the source explaining process design, operation conditions, material quality, and process scale; employing multiple third party reviewers; using verified data; and covering the relevant fiberglass insulation market.

The fiberglass insulation datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium

Fly Ash

The energy, emissions, and transportation factors of fly ash rely on one primary data source, EPA (2003c). This document pertains to life cycle GHG emissions factors for fly ash, particularly as a cement replacement in concrete, which is the use considered in WARM. EPA (2003c) is a medium-high quality source. Temporally this was a low-quality source, and the process review was medium-low quality as the document was only reviewed internally. Other indicators were high quality, including process completeness, data collection methods, technological correlation, and geographical correlation. Flow reliability was medium-high data quality, as data was based on verified calculations rather than verified measurements.

The fly ash fiberboard datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Medium-density Fiberboard

The medium-density fiberboard material emissions factors and energy factors utilize two sources: Wilson (2010) and Composite Panel Association (2018). Wilson (2010) plays a key role in determining life cycle emissions of medium-density fiberboard, and focused on manufacturing and transportation emissions, resources, energy, and carbon. Composite Panel Association (2018) informs the emissions factors of manufacturing medium-density fiberboard with virgin inputs.

Wilson (2010) was a medium-high quality source that had high quality indicators besides flow reliability, which was medium-high quality based on the use of calculations, and temporal correlation, which was medium-low quality as the source is over 10 years old. Composite Panel Association (2018) was a high-quality source as all process indicators and two flow indicators were found to be high quality. Three flow indicators, geographical correlation, temporal correlation, and flow reliability, were medium-high quality, as this source is over 5 years old, set in North America, and based on verified calculations.

The medium-density fiberboard datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Structural Steel

The assessment of material life cycle emissions for structural steel relies on six data sources: AISI (2016), AISI (2017), BTS (2013), EPA (1998), U.S. Department of Commerce (2020), World Steel Association (2020). Of these, AISI (2016) and AISI (2017) were key sources, and BTS (2013) and (EPA 2018) informed the data on structural steel but were also used to inform data on several other material types.

AISI (2016) is an environmental product declaration of fabricated hot-rolled structural steel sections. The source has an overall high quality flow representativeness. It has a high geographic correlation as it focuses on the American steel industry, and a medium temporal correlation as it was published within the last 10 years, although the report states the data has a five-year period of validity, which has expired. It also has high quality technological correlation and data collection methods, as the source examines a wide scale of technology categories and uses representative data from a high percentage of the market. The source had a medium-high quality flow reliability as it is an industry report based on estimated calculations, and high-quality process indicator data due to third party reviews and a large percent of process flows covered in the report, including data from all stages of the steel life cycle.

AISI (2017) is also a LCA report, focusing on structural section and hot-dip galvanized steel production in China. It was determined to have medium-high data quality. This is a comprehensive report based on verified measurements, giving it a high-quality flow reliability. The wide scope of flows and manufacturing processes covered, as well as the third-party review, resulted in this source having high quality process indicators. Finally, flow representativeness was also high quality, as technological correlation and data collection methods were both verified based on a wide variety of data sources and technology scopes related to the life cycle of steel. The lowest quality indicators for this source were temporal correlation, which was medium quality as the source is more than six but less than 10 years old, and geographic correlation, which was medium-low quality as the geographic focus is China.

The structural steel datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Vinyl Flooring

The assessment of material life cycle emissions for vinyl flooring relies on six data sources: Ecobilan (2001), Jones (1999), Lippiatt (2007), Baitz et al. (2004), FAL (2007), and BTS (2013). Of these, Lippiatt (2007), FAL (2007), and BTS (2013) are cross cutting sources that are also used to determine the emissions factors and energy factors of other material types, including drywall and fiberglass insulation. Two sources, Lippiatt (2007) and Baitz et al. (2004) are key sources to determining the life cycle emissions factors of vinyl flooring.

Baitz et al. (2004) is an LCA of materials that informs the composition and process emissions of vinyl flooring. Baitz et al. (2004) is considered a medium-high quality data source, as process indicators and data collection methods indicate high quality and flow reliability shows medium-high quality. As this is a European study conducted over 15 years ago, the temporal and geographic correlations were low or medium-low quality. The technological correlation of this study was deemed medium quality, as it addressed only two relevant technology categories.

Jones (1999) is an assessment of various flooring materials and provided information on the manufacturing process emissions for vinyl flooring. This was a medium-low quality source, one of the lowest ratings of all the construction materials data sources. This poor quality was due to its unspecified geographic region of study, publishing date of over 15 years ago, low quality data collection methods, and unknown percentage of flows evaluated. Most of the flow and process indicators were low quality, with others being at most medium quality.

The vinyl flooring datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium

Wood Flooring

Wood flooring materials emissions factor and energy factor calculation utilize six data sources to understand life cycle emissions: Bergman et al. (2013), American Wood Council (2013), BTS (2013), Bergman and Bowe (2008), Hubbard and Bowe (2008) and Athena Sustainable Materials Institute (2000). Of these, several sources also are used to inform data on multiple materials in addition to wood flooring: Bergman et al. (2013) and American Wood Council (2013) are sources for dimensional lumber; BTS (2013) is a source for vinyl flooring, fiberglass insulation, and drywall; and Athena Sustainable Materials Institute (2000) is also a source for asphalt shingles and fiberglass insulation. Three sources were determined to provide key information into the life cycle emissions of wood flooring materials: Bergman and Bowe (2008), Hubbard and Bowe (2008), and Athena Sustainable Materials Institute (2000).

Bergman and Bowe (2008) was deemed a medium-high quality source that considers manufacturing process emissions and material consumption of hardwood lumber, a primary material used for wood flooring. The study analyzes the environmental impact of hardwood lumber production in the United States by calculating data from industry estimates and information provided by 20 lumber mills. As there are hundreds of mills in the United States, this small sample means data collection method was deemed medium-low quality for this source. Also, the source is 15 years old, so it has low quality temporal correlation. Otherwise, process and flow indicators were of high or medium-high quality, averaging out into an overall medium-high quality source.

Hubbard and Bowe (2008) is a medium quality source with low quality temporal correlation as it is 15 years old and medium-low quality data collection methods due to a small sample size of the market. Hubbard and Bowe (2008) is also a study into the life cycle inventory of hardwood wood flooring materials, but it focuses specifically on the Eastern US, where the majority of lumber mills are located. Besides the lower temporal and data collection ratings, all other flow and process indicators are of high or medium-high quality.

The wood flooring datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Datasets for the individual construction materials ranged from medium-low to high quality, as noted at the end of each material sub-section. Overall, the construction material datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Recommendations

Areas for improvement include:

- Identify and update construction materials data sources to more recent sources, where applicable, based on the quality of the temporal correlation (medium-low or low data quality). Some sources may not have more recent versions, but updated data should be used if possible.
- Replace Jones (1999) from the sources for vinyl flooring materials with a more recent study that has higher quality process indicators, data collection methods, and geographic correlation. This is the lowest quality construction materials data source.
- Find additional data sources for fly ash materials to the one that is currently used to provide multiple sources that inform life cycle calculations of fly ash materials.

3.7 Tires

Summary of Key Findings

Data Sources. The tires material emission factors and energy factor calculations rely on 18 data sources for information regarding the different end uses of scrap tires, tire and scrap tire energy content, proportions of materials in scrap tires, and the process energy requirements of different end use techniques.

Key data sources for the tires material pathway in WARM include the following:

- Rubber Manufacturers Association (RMA) 2009 *Scrap Tire Markets in the United States: 9th Biennial Report*, which reviews the different end-of-life pathways for scrap tires and provides the share of all tires that go to each disposal pathway (RMA 2009a). **(KEY)**

- Atech Group's *A National Approach to Waste Tyres*, which provides the process energy requirements for new tires (Atech Group 2001). **(KEY)**

Supporting information on management pathways and their associated emissions as well as additional process emission data came from the following:

- California Integrated Waste Management Board's (CIWMB) *Tires as a fuel supplement: Feasibility study: Report to Legislature* report provides information on the energy content in tires used for calculations regarding tire combustion (CIWMB 1992).

- EIA's 2009 report on the fuel consumption requirements for new tires (EIA 2009).

- Venta and Nisbet's *Life Cycle Analysis of Residential Roofing Products* report, which provides offset energy values for sand used in rubber for tires (Venta and Nisbet 2000). These offsets were applied to end-of-life management pathway calculations.

- RMA's 2010 *Facts at a Glance: How a Tire is Made* report, which provides tire manufacturing energy requirements (RMA 2010a).

- Personal communication with RMA's Michael Blumenthal regarding the industry average scrap tire recovery rate in the US (RMA 2010b).

- RMA's 2009 *Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics* report (RMA 2009b), which provides the average weight of a scrap tire used in WARM calculations.

Additional sources were used to calculate end-of-life emissions from different management pathways and provided additional context in the supporting documentation chapter, including:

- Corti and Lombardi's 2004 report on the retention rate and energy required for a tire recycling process known as pulverization (Corti and Lombardi 2004).
- EPA's *Greenhouse Gas Emissions from the Management of Selected Materials* report, that included assumptions for the composition, uses, and energy of scrap tires. Information in this report is used for context in the supporting documentation chapter (EPA 1998).
- ICF's 2006 *Life-Cycle Greenhouse Gas Emission Factors for Scrap Tires* report. Information in this report is used for context in the supporting documentation chapter (ICF 2006).
- Nevada Automotive Test Center provided information on the retreading of tires and the associated energy required (Nevada Automotive Test Center 2006). Information in this report is used for context in the supporting documentation chapter.
- NIST's *MEP Environmental Program, Best Practices in Scrap Tires & Rubber Recycling* provided information on the composition of different fibers in tires to help calculate scrap tire's weight composition by material (NIST 1997).
- Praxair's 2009 report on cryogenic grinding of scrap tires was used for contextual information in the supporting documentation chapter (Praxair 2009).
- Pimentel et al.'s *U.S. Energy Conservation and Efficiency: Benefits and Costs* report provides information on synthetic rubber manufacturing as well as transportation requirements (Pimentel et al. 2002).

Finally, transportation emission factors were sourced from the following reports:

- FAL's 1994 *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* included transportation energy requirements in WARM calculations (FAL 1994).
- NREL's 2015 US Life Cycle Inventory Database provides retail transport requirements (NREL 2015).
- *U.S. Census Commodity Flow Survey* includes additional retail transport requirements for WARM calculations (BTS 2013).

Of the sources used in the tires section, two played key roles in determining process energy requirements and emission factors for various end of life scenarios: Rubber Manufactures Association (RMA — now the U.S. Tire Manufacturing Association) 2009 report on scrap tires and Atech Group's 2001 report. The RMA (2009a) source details what share of used tires go toward different end-of-life scenarios (e.g., combustion, reclamation, various recycling techniques) and the Aetch Group (2001) source provides process energy requirements for new tires to aid in source reduction calculations. The remaining sources are used to help fill in gaps in data or provide additional context on the waste management of tires in the documentation chapter. This includes detailed energy use data for different recycling strategies (Corti and Lombardi 2004) and combustion (CIWMB 1992), background information on tire disposal (EPA 1998), and transportation requirements (BTS 2013 and NREL 2015).

Scoring. The overall data quality levels of the 18 sources varied from medium to high. The variation is due in large part to differences in data collection methods, review process of the studies, and the data generation and validation methods used by the studies. Of the 18 sources, three could not be located as they were removed from their original web location due to branding changes by the source or untraceable written communications that were previously noted as email exchanges. These sources were: RMA (2010a), RMA (2010b), and Praxair (2009). Due to lack of information, they were given low data quality values for each DQI, with the exception of data year. The data quality results for tires are shown in Table 15, and details on the individual sources' scores can be found in the Appendix. The key findings for each of these sources are discussed below.

Table 15: Summary of Data Quality Results for Tires Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	Flow Represent-ativeness	Process Review and Completeness	Average	Weighted Average
Tires	Medium	Medium	Medium	**Medium**	**Medium**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Overall, temporal correlation and process review indicators received the lowest data quality values across the tire data sources, indicating the tires section would benefit from a literature review and data collection from newer sources that have undergone more extensive review. The average year of publication for the tires sources was 2004. The two key sources – RMA 2009 and Atech Group 2001 – had data quality values of medium-high and medium, respectively.

Overall, the tires datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium

Recommendations

Areas for improvement include:

- Update one of the key data sources for tires with an updated report by RMA on scrap tire management (released October 2022).
- Identify a recent source on tire process emissions to either corroborate or update the values from the Atech Group 2001 report.
- Locate replacement studies for those sources that could not be recovered.
- Update those sources with the oldest published dates, most notably CIWMB (1992), NIST (1997) and EPA (1998).

3.8 Food Waste

Summary of Key Findings

Data Sources. Food waste materials included in WARM include beef, poultry, grains, bread, fruits and vegetables, and dairy products. The data quality analysis for food waste involved a review of 17 data sources. Of these, the majority of process energy, process non-energy, and transportation emission factors data related to food waste rely on eight key data sources, which were weighted more heavily when assessing data quality due to their importance in WARM calculations:

- Beef
  - The report, *More Sustainable Beef Optimization Project* (Battagliese et al. 2013), submitted by BASF Corporation, which provides data on production energy and emissions for cradle to packing plant/case-ready plant gate. **(KEY)**
  - Email correspondence with Thomas Battagliese, BASF (February 2014), which provides updated data for the study, Battagliese et al. 2013 with revised boundaries. **(KEY)**
- Poultry
  - The journal article, *Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions*, Pelletier (2008), which provides data on cradle-to-farm gate energy and emission factors for poultry. **(KEY)**
  - The report, *What's at Steak? Ecological Economic Sustainability and the Ethical, Environmental, and Policy Implications for Global Livestock Production* (Pelletier 2010), which also provides data on cradle-to-farm gate energy and emission factors for poultry. **(KEY)**
- Grains and Bread
  - The journal article, *The Carbon Footprint of Bread* (Espinoza-Orias et al. 2011), which provides process emission and energy data on bread production. **(KEY)**
  - *Estimating Wheat Supply and Food Use*, prepared by the U.S. Department of Agriculture Economic Research Service (USDA 2012a), which provides grains supply data for the United States. **(KEY)**
- Fruits and Vegetables
  - *Comparison of Twelve Organic and Conventional Farming Systems: A Life Cycle Greenhouse Gas Emissions Perspective* (Venkat 2012), which provides data on cradle to farm GHG emissions from fruits and vegetables production. **(KEY)**
  - UC Davis fruits and vegetables cost production studies (Fake et al. 2009, O'Connell et al. 2009, Stoddard et al. 2007, Wunderlich et al. 2007), which provide production data for various fruits and vegetables. **(KEY)**
  - A life cycle assessment on bananas, providing banana production data (Luske 2010). **(KEY)**
  - Ecoinvent 2.0, providing potato production data. **(KEY)**
- Dairy Products
  - *Global Warming Potential of Fluid Milk Consumed in the US: A Life Cycle Assessment* (Thoma et al. 2010) of the Innovation Center for U.S. Dairy and University of Arkansas, which provides process emissions data on milk production. **(KEY)**

The non-key sources for food waste, including 4 sources that were not used as key sources for a category, are:

- Grains and Bread
    - Nemecek, T., and Kagi, T. (2007). Life Cycle Inventories of Agricultural Production Systems. Ecoinvent Report No. 15., which provides data on process emissions from grain drying.
- Fruits and Vegetables
    - *Apples, Bananas, and Oranges: Using GIS to Determine Distance Travelled, Energy Use, and Emissions from Imported Fruit* (Bernatz 2009), which provides data on energy and emissions impact from transportation of fruits and vegetables.
- Dairy Products
    - *Food Availability (per Capita) Data System – 2010*, prepared by the U.S. Department of Agriculture Economic Research Service (USDA 2012b), which provides data on dairy supply in the United States.

Scoring. Data source analysis was conducted by food waste category, and then averaged to show that, overall, sources for food waste were of medium to medium-high data quality. A summary of the results by high level data quality indicators is shown in Table 16. The key findings for each of these sources used for the different food waste categories are discussed below and details on the individual sources' scores can be found in the Appendix.

Table 16: Summary of Data Quality Results for Food Waste Data Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	**Flow Represent-ativeness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Beef	Medium-high	Medium-high	Medium	**Medium-high**	**Medium-high**
Poultry	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Grains	High	Medium	High	**Medium-high**	**Medium-high**
Bread	High	Medium	High	**Medium-high**	**Medium-high**
Fruits & Vegetables	Medium-high	Medium-high	Medium	**Medium**	**Medium**
Dairy Products	Medium-low	Medium	Medium	**Medium**	**Medium**
Food Waste (non-meat)	Medium-high	Medium	Medium-high	**Medium**	**Medium**
Food Waste (meat only)	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Food Waste	Medium-high	Medium	Medium-high	**Medium-high**	**Medium-high**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Beef

The WARM emissions factors and energy factors developed for the beef category rely on two sources: Battagliese et al. (2013), "More Sustainable Beef Optimization Project" and an email correspondence with Thomas Battagliese (2014). Battagliese et al. (2013) is a key source that provides information on the cradle-to-plant production process and production transportation emissions of beef. Email correspondence with Thomas Battagliese (2014) was a communication between ICF and Thomas Battagliese that provides updated data for the cradle to packing plant/case-ready plant gate process energy and emission factors in Battagliese et al. (2013) with revised boundaries that no longer consider retail CED & direct emissions, including removal of transport from that phase.

Battagliese et al. (2013) is a moderately old analysis conducted over ten years ago and has a medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators except third-party reviews (sub-category of Process Review and Completeness Indicators) and temporal correlation (sub-category of Flow-Representativeness Indicators). The email correspondence with Thomas Battagliese (2014) also has a medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators except process review and temporal correlation.

Poultry

WARM emissions factors and energy factors for poultry rely on two key sources: Pelletier (2008) and Pelletier (2010). Both sources provide energy and emission factors for a cradle-to-farm gate analysis of poultry production. Although both sources are relatively old (2008 and 2010), they have medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators except process review and temporal correlation.

Grains and Bread

Grain and bread food-waste categories rely on the same sources for WARM emissions and energy factors. Two sources, Espinoza-Orias et al. (2011), “The Carbon Footprint of Bread” and USDA (2012a), “Estimating Wheat Supply and Food Use” played a key role in understanding life cycle emissions and energy factors of grains and bread. Other sources included Nemecek and Kagi (2007), Life Cycle Inventories of Agricultural Production Systems, which provides life cycle inventory data on agricultural production processes and was used to inform the processing factors for grain drying. Espinoza-Orias et al. (2011) provided an analysis of the carbon footprint of bread and USDA (2012a) provided wheat supply and food usage data for the U.S.

Espinoza-Orias et al. (2011) has medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators however, it received low data quality scores for geographical correlation (sub-category of Flow Representativeness Indicators) as it is based in the UK. USDA (2012a) also has medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators, except temporal correlation, as it uses data that is older than 15 years. Nemecek and Kagi (2007) has medium data quality overall due to low data quality scores for temporal correlation and geographical correlation as the study is more than 15 years old and its data is representative of Switzerland.

Fruits and Vegetables

The production energy and emissions factors for fruits and vegetables rely on the following key sources: Venkat (2012), Comparison of Twelve Organic and Conventional Farming Systems: A Life Cycle Greenhouse Gas Emissions Perspective, UC Davis fruits and vegetables data, a LCA of bananas (Luske et al. 2010), and Ecoinvent data for potato production data. Venkat (2012) is a cradle-to-farm analysis providing life cycle GHG emissions for twelve crop products grown in California through organic and conventional farming systems. UC Davis fruits and vegetables data obtained from cost production studies (Fake et al. 2009, O'Connell et al. 2009, Stoddard et al. 2007, Wunderlich et al. 2007) informs production emissions for fruits and vegetables through research and analysis conducted at UC Davis using data from 2007-2009. Luske et al. (2010) and Ecoinvent were used for banana and potato production data, respectively. Bernatz (2009) provides production transportation emissions and energy factors for fruits and vegetables.

Venkat (2012) reflects medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators except temporary correlation and process review, as the study is more than 10 years old and lacks information on external reviews conducted. UC Davis fruits and vegetables data (Fake et al. 2009, O'Connell et al. 2009, Stoddard et al. 2007, Wunderlich et al. 2007) reflected medium to medium-low data quality overall due to range of data quality across the indicators. For each study, the data are currently 14 or more years old and there is a lack of information on external reviews conducted. Luske (2010) had medium data quality due to a combination of both higher and lower data quality values across the indicators. It is a comprehensive study with medium-high to high marks on flow reliability, technological correlation, data collection methods, and process completeness; however, lower data quality was noted due to the older age of the data and lack of documentation of a peer review. Ecoinvent Centre (2015) had medium-high data quality due in large part to their high-quality data generation methods, diligent review process, and recency of publishing. Bernatz (2009) had high and medium-high data quality values for most flows and process indicators except temporal correlation and process review, which were both low data quality.

Dairy Products

Thoma et al. (2010), "Global Warming Potential of Fluid Milk Consumed in the US: A Life Cycle Assessment," serves as a key source in the development of the life cycle emissions and energy factors for dairy products. It is a life cycle assessment that estimates the GHG emissions associated with milk consumed in the United States. Thoma et al. (2010) shows medium-high data quality overall due to high data quality for most flows and process indicators. The study received a medium-low data value for temporal correlation as it uses data more than ten years old. The source, USDA (2012b), "Food Availability (per Capita) Data System – 2010" aided in developing the proportion of food types in the U.S. waste stream. It had medium-high data quality due to high quality process completeness and data collection methods.

Overall, the food waste datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium

Recommendations

Areas for improvement include:

- Update all food waste data sources to more recent sources, where applicable, based on the quality of the temporal correlation (medium-low or low data quality). Some sources may not have more recent versions, but updated data should be used if possible.

- Update sources for beef and fruits and vegetables food waste categories to sources that have information on external reviews, based on the quality of process review (medium-low or low data quality).
- Replace Nemecek and Kagi (2007) from the sources for grains and bread with a more recent study that has higher temporal correlation, geographic correlation, and data collection methods. This is the lowest quality food waste data source.
- Find additional data sources to Thoma et al. (2010) to provide more sources informing life cycle operations of dairy products.
- Review and consider potential data sources referenced in EPA's Office of Research and Development 2021 report "From Farm to Kitchen: Environmental Impacts of Food Waste (Part 1)" as well as the upcoming release of Part 2.[18]

3.9 Yard Trimmings

Summary of Key Findings

Data Sources. The yard trimmings material emission and energy factors calculations rely on seven data sources for information regarding the different characteristics and treatments of yard trimmings, including carbon storage calculations, data on biodegradability, and solid waste treatment techniques.

Key data sources for the yard trimmings material pathway in WARM include the following:

- *Systematic evaluation of industrial, commercial, and institutional food waste management strategies in the United States*, published in Environmental Science & Technology (Hodge et al. 2016), which evaluates waste management strategies used in the United States and provides process emission and energy data for waste management pathways of organic waste. **(KEY)**

- *Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills*, published in Global Biogeochemical Cycles (Barlaz 1998), which provides data on carbon storage during biodegradation of yard trimmings.[19] **(KEY)**

- EPA report, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (EPA 2006), which provides life-cycle emissions and energy data for yard trimmings collection and management. **(KEY)**

- *IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste, Chapter 3: Solid Waste Disposal* (IPCC 2006), which provides data on N_2O emissions from combustion of MSW. **(KEY)**

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[18] https://www.epa.gov/land-research/farm-kitchen-environmental-impacts-us-food-waste

[19] Barlaz (1998) is also a source for data for the landfill pathway in WARM.

Non-key data sources for the yard trimmings material pathway in WARM include the following:

- *The Role of Recycling in Integrated Solid Waste Management to the Year 2000*, prepared by Franklin Associates, Ltd. (FAL 1994), which provides data on transportation emissions.

- EPA report, *Advancing Sustainable Materials Management: Facts and Figures 2015* (EPA 2018a), which provides statistical data on U.S. yard trimmings generation and treatment.

- *Landfill Gas Monte Carlo Model Documentation and Results*, published by the EPA (Levis and Barlaz 2014), which provides data on landfill gas collection efficiency.

Scoring. A summary of the results by data quality indicator groupings for yard trimmings is shown in Table 17**Error! Reference source not found.**. The key findings for each of these sources are discussed below.

Table 17: Summary of Data Quality Results for Yard Trimmings Data Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	**Flow Represent-ativeness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Yard Trimmings	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Hodge et al. (2016) has medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators. Although Barlaz (1998) reflects medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators, it uses relatively old data (1998) and has a low data score for temporal correlation (sub-category of Flow Representativeness Indicators). Both EPA (2006) and IPCC (2006) have medium-high data quality overall but uses data more than 17 years old and EPA (2006) lacks information on external reviews. Levis & Barlaz (2014) has medium-high data quality overall due to high and medium-high data quality scores for most flows and process indicators except process review (sub-category of Process Review and Completeness Indicators) due to lack of information on external reviews. Both sources, FAL (1994) and EPA (2018a), reflect medium-high data quality overall due to high and medium-high data quality values for most flows and process indicators.

Overall, the yard trimmings datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Additional details on the scoring results from the assessment of the flow level and process level indicators for the yard trimmings datasets are presented in the Appendix table.

Recommendations

Areas for improvement include:

- Update data sources used from Barlaz (1998) and FAL (1994) to more recent sources, based on the low data quality of the temporal correlation. Both these sources may not have more recent versions, but updated data should be used if possible.

4. Assessment of Specific Management Pathway Datasets

The following sections present the results from the assessment of the quality of the datasets and data sources by management pathway of landfilling, composting, combustion, and anaerobic digestion. Separate sections are not included for source reduction or recycling as the relevant data sources are already included under the respective material assessment sections. Summaries of key findings are presented followed by recommended areas for further research and improvement of the data quality. In the discussion of data sources, key sources used in the development of the emission and energy factors are noted as **(KEY)**. They are weighted more heavily for the development of the weighted averages. Additional details on the scoring results from the assessment of the flow level and process level indicators for each management pathway data source are presented in the Appendix: Data Quality Assessment Matrix.

4.1 Landfilling

Summary of Key Findings

Data Sources. To understand landfilling emissions factors, WARM accounts for material composition, component-specific decay rates, anaerobic decomposition, landfill gas collection, and overall landfill emissions, including carbon dioxide, methane, and volatile organic compounds. The modeling of the landfilling waste management pathway in WARM underwent significant revisions in 2013-2014 that were first incorporated into the June 2014 release of WARM version 13. The management pathway emissions factors for landfilling rely on a total of 10 sources, including the following five key government-published or academic peer-reviewed journal articles:

- *What is the optimal way for a suburban U.S. city to sustainably manage future solid waste? Perspectives from a Solid Waste Optimization Life-cycle Framework (SWOLF)*, published by North Carolina State University's Department of Civil, Construction, and Environmental Engineering (Levis et al. 2013), which provides information on landfill carbon emissions. **(KEY)**
- *Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills*, published in Global Biogeochemical Cycles (Barlaz 1998), which provides data on landfill methane, carbon dioxide, and material decomposition emissions.[20] **(KEY)**
- *Decomposition of Forest Products Buried in Landfills*, published in Waste Management (Wang et al. 2013), which provides insight into material decomposition. **(KEY)**

[20] Barlaz (1998) is also a data source for yard trimmings material emissions factors.

- *Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data*, published in Environmental Science & Technology (De la Cruz and Barlaz 2010), which provides component-specific decay rates. **(KEY)**
- *Landfill Gas Monte Carlo Model Documentation and Results*, published by the EPA (Levis and Barlaz 2014), which provides data on landfill gas collection. **(KEY)**

Five other non-key sources also informed management pathway emissions factors for landfilling:

- *Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills,* published in Environmental Science (Freed et al. 2004), which provides information on anaerobic decomposition and landfill emissions.
- *The Production of Methane from Solid Wastes,* published in the Journal of Geophysical Research (Bingemer and Crutzen 1987), which provides data on landfill carbon dioxide and methane emissions.
- *Characterization of landfill gas composition at the Fresh Kills municipal solid-waste landfill,* published in Environmental Science & Technology (Eklund et al. 1998), which provides measurement data on volatile organic compounds (VOCs) in landfill gas samples.
- *Wood Biodegradation in Laboratory-Scale Landfills,* published in Environmental Science Technology (Wang et al. 2011), which provides information on material decomposition.
- Greenhouse Gas Reporting Program (GHGRP), published on EPA.gov (EPA 2018c), is an EPA program that requires businesses and others to report data on GHG emissions from major industrial sources in the United States. It includes estimates on the amount of methane generated by U.S. landfills.

Scoring. A summary of the results by the high-level data quality indicators is shown in Table 18. The key findings for each of these sources used for the different landfilling management pathways are discussed below.

Table 18: Summary of Data Quality Results for Landfilling Data Sources

Management Pathway	DQ Values by Indicator Grouping				
	Flow Reliability	Flow Represent-ativeness	Process Review and Completeness	Average	Weighted Average
Landfilling	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**

The data quality of these sources was medium-high. On average, the indicator with the highest data quality was geographical correlation, as many of these sources referenced U.S.-based data. Other high-quality indicators include process completeness, data collection methods, and technological correlation, indicating that the landfilling sources represent a large sample of landfilling management pathways, using a large percentage of flows and technology types.

The lowest quality indicator for landfilling was temporal correlation, which was deemed to be medium-low quality. Many of these sources are over 10 years old, and several are over 15 years old, giving them medium-low or low quality temporal correlation. Yet despite this lower quality indicator, the other flow and process indicators were of medium high quality.

The highest quality sources were two of the key sources, Levis and Barlaz (2014) and Wang et al. (2013), and one other source, De la Cruz and Barlaz (2010). All of these sources had high data quality scores. Levis and Barlaz (2014) provided information on landfill gas collection, Wang et al. (2013) focused on material decomposition, and De la Cruz and Barlaz (2010) focused on component-specific decay rates.

Overall, the landfilling datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Recommendations

- Update landfilling data sources to more recent sources where applicable, based on the quality of the temporal correlation (medium-low or low data quality). Some sources may not have more recent versions, but updated data should be used if possible.

4.2 Composting

Summary of Key Findings

Data Sources. WARM considers fugitive emissions from composted material, emissions from food and yard waste, the composition of the composting waste stream, and the capacity for carbon storage in compost-soil for the development of composting emissions factors. The assessment of management pathway life cycle emissions for composting relies on seven data sources. Four of these sources played a key role in informing process emissions and weighed more heavily when determining overall data quality of composting:

- *Evaluation of Climate, Energy, and Soils Impacts of Selected Food Discards Management Systems,* published by the State of Oregon Department of Environmental Quality (Oregon Department of Environmental Quality 2014), which provides information on composting emissions from food waste. **(KEY)**

- *Impact of Composting Food Waste with Green Waste on Greenhouse Gas Emissions Compost Windrows*, published in Compost Science & Utilization (Williams et al. 2019), which provides data on fugitive emissions from composted waste. **(KEY)**

- *The Role of Recycling in Integrated Solid Waste Management to the Year 2000,* prepared for Keep America Beautiful, Inc. by Franklin Associates, Ltd. (FAL 1994), which provides measurements of composting emissions from yard waste. **(KEY)**

- *U.S. Life Cycle Inventory Database,* published by the National Renewable Energy Laboratory (NREL 2015), which provides food and yard waste emissions data.[21] **(KEY)**

[21] The data quality of NREL (2015) was assessed based on information provided in the abstract.

Three non-key sources were also used to provide data on composting process emissions:

- *Greenhouse gas emissions from composting and mechanical biological treatment,* published in Waste Management & Research (Amlinger at al. 2008), which provides measurements of composting GHG emissions.
- *Formation and Emission of N2O and CH4 from Compost Heaps of Organic Household Waste,* published in Waste Management & Research (Beck Friis et al. 2000), which provides data on carbon storage in composted soil.
- EPA'*s MSW Facts and Figures* (EPA 2014), which informed the composition of the composting waste stream used in the calculations of the PLA and mixed organics factors.

Two of the above sources were also used to inform other aspects of WARM: Oregon Department of Environmental Quality (2014) was also a data source for bioplastics, and FAL (1994) was a source for bioplastics, tires, and combustion.

Scoring. A summary of the results by high level data quality indicators is shown in Table 19Table 18. The key findings for each of these sources used for the different composting management pathways are discussed below.

Table 19: Summary of Data Quality Results for Composting Data Sources

Management Pathway	DQ Values by Indicator Grouping				
	Flow Reliability	Flow Represent-ativeness	Process Review and Completeness	Average	Weighted Average
Composting	Medium-high	Medium	High	Medium-high	Medium-high

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

The quality of these data sources ranges from medium to high. This is due to high quality indicators, including flow reliability, process review, and process completeness. Data collection methods, an indicator under flow-representativeness, was also determined to be high quality, although overall flow representativeness was deemed to be medium quality, due to low temporal indicator quality.

The lowest quality indicator was temporal correlation, part of the flow representativeness indicators category, as three of the composting sources are over 15 years old, and one is over 10 years old. This resulted in composting data sources generally having a medium quality temporal correlation.

The highest quality composting data source was NREL (2015), a high-quality source due to its high-quality process indicators, data collection methods, and geographic correlation. However, the temporal correlation was determined to be medium quality, as the source is eight years old, which falls into the medium quality range of five to ten years old. All other sources had an average indicator quality of high or medium-high.

Overall, the composting datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Recommendations

- Update all composting data sources to more recent sources where applicable, based on the quality of the temporal correlation (medium-low or low data quality). Some sources may not have more recent versions, but updated data should be used if available.
- Review and consider additional sources that collect and analyze recent data on food waste in the United States, such as the U.S. EPA's 2019 Wasted Food Report,[22] which estimates how food waste is managed across the nation through several pathways, including composting and aerobic processes. Also review and consider potential data sources referenced in EPA's Office of Research and Development 2021 report "From Farm to Kitchen: Environmental Impacts of Food Waste (Part 1)" as well as the upcoming release of Part 2.[23]
- Identify another source for the composition of the composting waste stream in the United States as the EPA Facts and Figures methodology changes.

4.3 Combustion

Summary of Key Findings

Data Sources. The combustion management pathway emissions and energy factors rely on 18 data sources. Of the sources used for combustion, eight played key roles in determining the energy consumption and emissions from combustion including:

- The BioCycle report, *The State of Garbage in America* (Van Haaren et al. 2008), which provides data on the percentage of textile discards treated with combustion in the United States and the non-biogenic carbon content of plastic, textiles, rubber and leather. **(KEY)**

- *Climate Change 2007: The Physical Science Basis* report (IPCC 2007), which provides N_2O emission estimates from MSW combustors. **(KEY)**

- *Environmental impact of producing hardwood lumber using life-cycle inventory*, published in Wood and Fiber Science (Bergman and Bowe 2008), which provides energy content data for wood flooring combustion. **(KEY)**

- *Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume* (Gaines and Stodolsky 1993), which provides data on energy content of specific materials combusted under the MSW category. **(KEY)**

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[22] https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/food-material-specific-data
[23] https://www.epa.gov/land-research/farm-kitchen-environmental-impacts-us-food-waste

- *Estimation of the Effects of Various Municipal Waste Management Strategies on Greenhouse Gas Emissions* (Procter and Redfern, Ltd. & ORTECH International 1993), which provides data on energy content and emissions of specific materials combusted under the MSW category. **(KEY)**

- *Data Summary of Municipal Solid Waste Management Alternatives* (NREL 1992), which provides data on the energy content of refuse derived fuel (RDF) and combustion system efficiency of RDF plants. **(KEY)**

- *Project Fire Model. Summary Progress Report-II* (Fons et al. 1962), which provides energy content data for dimensional lumber and fiberboard combustion. **(KEY)**

- "The role of using carpet as a fuel in carpet recovery system development" (Realff 2010), which provides energy content data for carpets and tires combustion. **(KEY)**

An additional source that was used to calculate material recovery from combustion:

- Personal communications between ICF and Covanta Energy (Bahor 2010), which provides data on amount of steel and ferrous metal recovered per ton of mixed MSW combusted.

Finally, emission factors for transportation of waste and ash were sourced from the following reports:

- FAL's 1994 *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* included transportation energy requirements in WARM calculations (FAL 1994).

- NREL's 2015 US Life Cycle Inventory Database provided retail transport requirements (NREL 2015).

Six data sources could not be located and thereby were deemed low quality:

- Personal communication between the Fiber Economics Bureau and ICF (DeZan 2000), which provides data on non-biogenic share of carbon in textiles.

- Incropera, F. P., & DeWitt, D. P. (1990). Introduction to Heat Transfer, Second Edition. New York: John Wiley & Sons, pp. A3-A4, which provides specific heat data of materials that is used to calculate the energy content of materials combusted.

- Personal communication with the Integrated Waste Services Association (Zannes 1997), which provides data on combustion system efficiency of mass burn plants.

- Personal communication with Minnesota Office of Environmental Assistance (Harrington 1997), which provides data on combustion system efficiency and energy content of RDF.

- *The 2000 [Integrated Waste Services Association] IWSA Waste-To-Energy Directory of United States Facilities* (IWSA 2000), which provides data on combustion system efficiency of RDF plants.

- Personal communication between IWSA, American Ref-Fuel, and ICF (IWSA & American Ref-Fuel (1997), which provides data on energy content of mixed MSW combusted and losses in transmission and distribution of electricity specific to WTE combustion facilities.

Scoring. A summary of the results by high level data quality indicators is shown in Table 20**Error! Reference source not found.**. The key findings for each of these sources used for the different combustion management pathways are discussed below.

Table 20: Summary of Data Quality Results for Combustion Data Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	**Flow Represent-ativeness**	**Process Review and Completeness**	**Average**	**Weighted Average**
Combustion	Medium	Medium	Medium	**Medium**	**Medium**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

In general, key sources for combustion had higher data quality results relative to the full set of sources leading to a slightly higher weighted average data quality value of medium relative to the average across the data sources of medium-low. Five of the eight key sources (Van Haaren et al. 2008, EPA 2018a, NREL 1992, IPCC 2007, and Bergman and Bowe 2008) had medium-high data quality receiving medium to high data results for most DQIs; however, they are older sources, which affected their temporal correlation data quality. NREL (1992), Van Haaren et al. (2008), and EPA (2018a) also lack information on external reviews giving them low data quality for the process review DQI sub-category. Overall, the data quality of Gaines and Stodolsky's (1993) study is medium due to several reasons. Because it is a relatively old source, it has low data quality for temporal correlation. In addition, it lacks a comprehensive discussion on data collection methods (sub-category of Flow Representativeness Indicators) and information on external reviews, which contributes to low data quality for process review. However, it received medium-high to high data quality results on other DQIs. Procter and Redfern, Ltd. & ORTECH International (1993) had medium data quality overall with a range of results across the DQIs, receiving medium high to high data quality results for process completeness, flow reliability and technological correlation, and low data quality for temporal and geographical correlation. Fons et al. (1962) has medium data quality overall as it is an old source and lacks a comprehensive discussion on data collection methods; however, it had medium-high to high data quality for several other DQIs. Details on the results for other data sources are included in the Appendix: Data Quality Assessment Matrix. The sources that could not be located were assigned a low data quality score.

Overall, the combustion datasets scored as follows:

- **Average indicator:** Medium
- **Average weighted indicator:** Medium

Recommendations

- Update all combustion data sources to more recent sources where applicable, based on the quality of the temporal correlation (medium, medium-low, or low data quality). Some sources may not have more recent versions, but updated data should be used if possible.

- Consider contacting authors to confirm whether external or internal reviews occurred where documentation is lacking on this. If reviews were not conducted, sources should be updated to more recent versions with reviews or replaced with sources with documentation of external reviews.

4.4 Anaerobic Digestion

Summary of Key Findings

Data Sources. The anaerobic digestion management pathway emissions and energy factors rely on seven data sources. Of the sources used for combustion, five played key roles in determining the energy consumption and emissions from anaerobic digestion including:

- *Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills* (Barlaz 1998), which provides data on carbon storage that occurs during biodegradation of MSW components in landfills. **(KEY)**

- *Formation and Emission of N_2O and CH_4 from Compost Heaps of Organic Household Waste* (Beck-Friis et al. 2000), which provides data on nitrous oxide and methane emissions from compost heaps of organic household waste. **(KEY)**

- *Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE* (Boldrin et al. 2011), which provides data on the environmental impacts of biological treatment of organic municipal waste. **(KEY)**

- The Landfill Methane Outreach Program (LMOP) LFGE Benefits Calculator (EPA 2013), which is a landfill gas energy benefits calculator used to estimate direct, avoided, and total GHG reductions as well as environmental and energy benefits from a landfill gas (LFG) energy project. **(KEY)**

- *Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution* (Møller et al. 2009), which provides GHG emissions data for anerobic digestion. **(KEY)**

An additional source was used to evaluate the chemical composition of material in household waste:

- *Chemical composition of material fractions in Danish household waste* in Waste Management (Riber et al. 2009).

Finally, values for GHG emissions resulting from fossil fuels used in vehicles collecting and transporting waste to the anaerobic digestion facility were sources from:

- NREL's 2015 US Life Cycle Inventory Database provided retail transport requirements (NREL 2015).

Scoring. A summary of the results by high level data quality indicators is shown in Table 21. The key findings for each of these sources used for the different anaerobic management pathway are discussed below.

Table 21: Summary of Data Quality Results for Anaerobic Digestion Data Sources

Material	DQ Values by Indicator Grouping				
	Flow Reliability	Flow Represent-ativeness	Process Review and Completeness	Average	Weighted Average
Anaerobic Digestion	Medium-high	Medium	Medium-high	**Medium-high**	**Medium**

Note: For details on the indicator subcategories for each indicator grouping, see Section 2: Approach.

Among the key sources, EPA (2013) and Barlaz (1998) had overall medium-high data quality. EPA (2013) had high data quality results for geographical and technological correlation, data collection methods and process completeness. It had lower data quality for temporal correlation and process review due to the source being more than ten years old and lacking documentation for external or internal reviews. Barlaz (1998) had high data quality results for five of the seven DQIs (flow reliability, geographical correlation, technological correlation, data collection methods, and process completeness). Its low data quality result was for temporal correlation as it is a relatively old source published more than fifteen years ago. Boldrin et al. (2013) had an overall medium data quality due to low data scores for temporal and geographical correlation (sub-categories of Flow Representatives Indicators). The source is over ten years old and is based in Denmark. Møller et al. (2009) had overall medium data quality with medium-high to high data quality results for flow reliability, technological correlation, and the process indicators, and low data quality results for temporal and geographical correlation as it is over ten years old and is based in Denmark. Beck-Friis et al. (2000) had an overall medium-low data quality as it is a relatively old source affecting its temporal correlation. Its data quality was low for geographical correlation, data collection methods (with focus on limited number of compost heaps), and process review.

Overall, the anaerobic digestion datasets scored as follows:

- **Average indicator:** Medium-high
- **Average weighted indicator:** Medium-high

Recommendations

- Update all anaerobic digestion data sources to more recent sources where applicable, based on the quality of the temporal correlation (medium, medium-low, or low data quality) and to sources with documentation of external reviews. Some sources may not have more recent versions, but updated data should be used if possible.

5. Conclusion

This report provided a comprehensive assessment of data quality for the numerous data sources used to develop the emission and energy factors for EPA's WARM. Table 22 summarizes the results by material category and management pathway for the DQI indicator groupings as discussed in the previous sections. In general, overall data quality was found to be medium or medium-high depending on the material type or pathway, with the exception of glass, paper, and carpet.

Table 22: **Summary of Data Quality Results by Material Type or Management Pathway**

Material or Pathway	DQ Values by Indicator Grouping				
	Flow Reliability[a]	Flow Represent-ativeness[b]	Process Review and Completeness[c]	Average[d]	Weighted Average[e]
Material Category					
Plastics	Medium-high	Medium-high	Medium	**Medium-high**	**Medium-high**
Bioplastics	Medium-high	Medium	Medium-high	**Medium-high**	**Medium-high**
Metals	Medium	Medium	Medium	**Medium**	**Medium**
Glass	Medium	Medium	Medium	**Medium**	**Medium-low**
Paper	Medium-low	Medium	Medium-low	**Medium-low**	**Medium**
Electronics	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Construction Materials	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Asphalt Concrete	*Medium-high*	*Medium*	*Medium-high*	***Medium-high***	***Medium***
Asphalt Shingles	*Medium-low*	*Medium*	*Medium*	***Medium***	***Medium***
Carpet	*Medium*	*Medium-low*	*Medium-low*	***Medium-low***	***Medium***
Clay Bricks	*Medium-high*	*Medium-high*	*High*	***Medium-high***	***High***
Concrete	*High*	*Medium-high*	*Medium*	***Medium-high***	***Medium-high***
Dimensional Lumber	*Medium-high*	*Medium-high*	*High*	***Medium-high***	***Medium-high***
Drywall	*Medium-high*	*Medium-high*	*Medium-high*	***Medium-high***	***Medium-high***
Fiberglass Insulation	*Medium*	*Medium*	*Medium*	***Medium***	***Medium***
Fly Ash	*Medium-high*	*Medium-high*	*Medium*	***Medium-high***	***Medium-high***
Medium-density Fiberboard	*Medium-high*	*Medium-high*	*High*	***Medium-high***	***Medium-high***
Structural Steel	*Medium-high*	*Medium-high*	*Medium-high*	***Medium-high***	***Medium-high***
Vinyl Flooring	*Medium-high*	*Medium*	*Medium-high*	***Medium***	***Medium***
Wood Flooring	*Medium-high*	*Medium*	*Medium-high*	***Medium-high***	***Medium-high***
Tires	Medium	Medium	Medium	**Medium**	**Medium**
Food Waste (non-meat)	Medium-high	Medium	Medium-high	**Medium**	**Medium**
Food Waste (meat)	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Yard Trimmings	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Management Pathway[f]					
Landfilling	Medium-high	Medium-high	Medium-high	**Medium-high**	**Medium-high**
Composting	Medium-high	Medium	High	**Medium-high**	**Medium-high**
Combustion	Medium	Medium-low	Medium	**Medium**	**Medium**
Anaerobic Digestion	Medium-high	Medium	Medium-high	**Medium-high**	**Medium**

[a]Refers to data generation method and verification.
[b]Includes temporal correlation (data year), geographical correlation (region of data), technological correlation (technology type, scale), and data collection methods (representativeness, sample size).
[c]Includes process review (third party or internal reviewers) and process completeness (percent of flows covered).
[d]Average of all indicators.
[e]Developed to give additional weight to the key data sources informing the emission factor estimates.
[f]Separate data quality assessments for source reduction and recycling were not conducted as their data sources were already captured under the material-specific data assessments.

This assessment identified a number of areas for improvements to update the underlying datasets that would improve the factors in WARM. These were described in each material and pathway subsection. A few overarching recommendations include the following:

- Identify more recent data sources for several materials and ensure that any updated publications are used.
- Prioritize the identification of publicly-available data sources.
- Identify published data sources to update certain data inputs.
- Prioritize updates to the modeling of glass, paper, metals, food waste (non-meat), carpet, asphalt shingles, fiberglass insulation, vinyl flooring, tires, and combustion based on both the average and weighted average data quality results for those categories, which fell below those of the other material or management pathway categories.
- Improve the archiving, referencing, and accessibility of the underlying data sources.
- Communicate the DQA findings alongside the WARM documentation.

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Appendix: Data Quality Assessment Matrix

The table below provides the detailed results on the scoring for each data source following the ORD Guidance scoring approach. Low scores equate with high data quality.

Summary of Data Quality Assessment by Material Type and Management Pathway

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	**Reference**	**Data generation method & verification**	**Data year**	**Region of data**	**Technology type, scale**	**Representativeness, sample size**	**Third party or internal reviewer(s)**	**% of flows covered**			
IDEAL SCORE		1	1	1	1	1	1	1	7	1	1
Plastics [a]	**Average Score**	**2.0**	**3.7**	**1.7**	**1.7**	**1.3**	**4.0**	**2.3**	**16.7**	**2.3**	**2.2**
Process energy emissions to manufacture Virgin HDPE, LDPE, PET, LLDPE, PP	FAL 2011	1	5	1	2	1	5	1	14	2.3	Y
Process energy emissions to manufacture Virgin GPPS, PVC	FAL 2011	1	5	1	2	1	5	1	16	2.3	Y
Process energy emissions to manufacture Recycled PET, HDPE, and PP	FAL 2018	2	2	2	1	1	3	1	12	1.7	Y
Retail transportation distance and fuel-type	BTS 2013	3	4	2	2	2	4	5	22	3.1	
Bioplastics [a]	**Average Score**	**2.0**	**4.5**	**2.3**	**1.5**	**1.8**	**1.8**	**2.0**	**15.8**	**2.2**	**2.2**
Process energy and emissions for PLA production	NatureWorks 2010	1	4	2	2	2	1	1	13	1.9	Y
Process energy and emissions for PLA production	Erwin Vink's responses 2010	1	4	1	2	2	3	2	15	2.1	Y
Transportation energy usage	FAL 1994	2	5	1	1	2	1	1	13	1.9	
Retail transportation distance and fuel-type	BTS 2013	3	4	2	2	2	4	5	22	3.1	
Transportation emissions	Oregon DEQ (2014)	2	5	4	1	1	1	1	15	2.1	

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	Reference	Data generation method & verification	Data year	Region of data	Technology type, scale	Representativeness, sample size	Third party or internal reviewer(s)	% of flows covered			
Metals [a]	**Average Score**	**3.0**	**4.6**	**1.8**	**2.0**	**3.6**	**3.2**	**3.3**	**21.5**	**3.1**	**2.9**
Aluminum Cans/Ingot	***Average Score***	***2.8***	***4.4***	***2.0***	***2.0***	***3.2***	***2.9***	***2.6***	***19.9***	***2.8***	***2.6***
Process energy and process non-energy data for manufacturing, recovery, and recycling	PE Americas 2010	2	4	1	1	2 (cans); 3 (ingot)	2	1	13 (cans); 14 (ingot)	1.9 (cans); 2.0 (ingot)	Y
Transportation energy data	RTI 2004	5	5	5	5	5	5	5	35	5.0	
Retail transportation energy data	EPA 1998b	2	5	1	1	4	2	1	15.5	2.2	
Retail transportation distance and fuel-type	BTS 2013	3	4	2	2	2	4	5	22	3.1	
Steel Cans	***Average Score***	***3.7***	***4.8***	***2.4***	***2.4***	***4.2***	***3.9***	***3.4***	***24.8***	***3.5***	***3.2***
Steel cans process energy and process non-energy, transportation energy	EPA 1998a	5	5	1	1	5	4	1	22	3.1	Y
Current mix of steel can production and recycled contents of production	FAL 2003a	4	5	3	3	5	5	5	30	4.2	
Steel Cans loss rates	FAL 2003b	5	5	5	5	5	5	5	35	5.0	
Retail transportation energy data	EPA 1998b	2	5	1	1	4	2	1	15.5	2.2	
Retail transportation distance and fuel type	BTS 2013	3	4	2	2	2	4	5	22	3.1	
Copper	***Average Score***	***2.5***	***4.5***	***1.3***	***1.5***	***3.0***	***3.0***	***4.0***	***19.8***	***2.8***	***3.0***
Process energy, process non-energy, and transportation energy	FAL 2002	4	5	1	2	5	2	5	24	3.4	Y
% of current production from recycled vs. "virgin" inputs, copper wire scrap mix used to create copper ingot.	USGS 2004	1	4	1	1	2	4	5	18	2.6	
Retail transportation energy data	EPA 1998b	2	5	1	1	4	2	1	15.5	2.2	
Retail transportation distance and fuel type	BTS 2013	3	4	2	2	2	4	5	22	3.1	
Glass [a]	**Average Score**	**3.5**	**4.8**	**2.5**	**2.5**	**3.7**	**3.0**	**3.0**	**23**	**3.3**	**3.5**

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	Reference	Data generation method & verification	Data year	Region of data	Technology type, scale	Representativeness, sample size	Third party or internal reviewer(s)	% of flows covered			
Process energy and process non-energy	RTI 2004	5	5	5	5	5	5	5	35	5.0	Y
Composition of glass and fuel used to combust glass	DOE 2002	4	5	1	1	5	1	1	18	2.6	
Current mix of production from virgin and recycled inputs and glass loss rates	FAL 2003b	5	5	5	5	5	5	5	35	5.0	
Transportation energy usage	FAL 1994	2	5	1	1	2	1	1	13	1.9	
Retail transportation distance and fuel type	BTS 2013	3	4	2	2	2	4	5	22	3.1	
Transportation fuel efficiencies	EPA 1998b	2	5	1	1	4	2	1	15.5	2.2	
Paper	**Average Score**	**4**	**5**	**3**	**3**	**4**	**4**	**3**	**25**	**3.50**	**3.48**
Energy and process emissions	RTI (2004)	5	5	5	5	5	5	5	35	5.0	Y
Process emissions	EPA (1998a)	5.0	5.0	1.0	1.0	5.0	4.0	1.0	22	3.1	Y
Composition of Mixed Paper Categories	FAL (1998)	2	5	1	1	3	2	1	15	2.1	Y
Current mix of recycled content	FAL 2003a	4	5	3	3	5	5	5	30	4.2	
Current mix of production from virgin and recycled inputs	FAL 2003b	5	5	5	5	5	5	5	35	5.0	
Transportation Energy	BTS (2013)	3	4	2	2	2	4	5	22	3.1	
Fuel-specific carbon content/co-efficients	EPA (2015)	4	4	1	1	1	1	1	13	1.9	
Electronics	**Average Score**	**2**	**3**	**2**	**1**	**3**	**2**	**1**	**16**	**2.3**	**2.2**
Cellphone materials and LCA	Andrea and Vaija (2014)	2	3	4	1	4	2	1	17	2.4	
Process emissions for electronic components	ANL (2018)	2	2	1	1	1	1	1	9	1.3	Y
Component mass share of electronics	Babbitt et al. (2017)	1	2	1	2	1	1	1	9	1.3	Y

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	**Reference**	**Data generation method & verification**	**Data year**	**Region of data**	**Technology type, scale**	**Representativeness, sample size**	**Third party or internal reviewer(s)**	**% of flows covered**			
Recycling emissions for electronic types	Bigum et al. (2012)	2	4	4	1	1	3	1	16	2.3	
Recycling emissions from lithium cobalt oxide batteries	Dewulf et al. (2010)	1	4	4	2	5	3	1	20	2.9	
Process emissions for metals in electronics	Ecoinvent Centre (2015)	1	3	4	1	1	1	1	12	1.7	Y
General electronic disposal information	EPA (2008)	2	5	1	1	1	5	1	16	2.3	
Fate of plastic in recycled electronics	FAL (2018)	2	2	2	1	1	3	1	12	1.7	
Virgin production of plastic and recycled plastic in electronics	FAL (2011a)	2	4	2	1	1	3	1	14	2.0	
LCI of postconsumer HDPE and PET	FAL (2011b)	2	4	1	2	1	3	1	14	2.0	
Process energy, process non-energy, and transportation energy for virgin and recycled copper	FAL (2002)	4	5	1	2	5	2	5	24	3.4	
Component mass share of electronics	Hikwama (2005)	2	5	3	1	5	5	1	22	3.1	
Mixed electronics share estimate	Mars et al. (2016)	4	3	4	1	5	1	1	19	2.7	
Virgin production emissions for printed circuit boards, flat panel display modules, and batteries	Teehan and Kandlikar (2013)	2	3	2	1	5	3	1	17	2.4	Y
CRT materials recovered from recycling	Turner et al. (2015)	4	3	1	1	5	1	1	16	2.3	
Emission information on LCD TVs	Vanegas et al. (2015)	4	3	3	3	5	2	1	21	3.0	
Construction Materials											
Asphalt Concrete	**Average Score**	**2**	**5**	**2**	**1**	**2**	**3**	**1**	**16**	**2.3**	**2.7**
Composition of hot mix asphalt	Hassan (2009)	2	5	1	1	5	5	1	20	2.9	Y
Material and fuel mix inputs	US Census Bureau (1997)	1	5	1	1	1	1	1	11	1.6	

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	**Reference**	**Data generation method & verification**	**Data year**	**Region of data**	**Technology type, scale**	**Representativeness, sample size**	**Third party or internal reviewer(s)**	**% of flows covered**			
Limestone manufacturing energy use	NREL (2009)	2	5	1	1	1	4	1	15	2.1	
Process Emissions Factors	Athena Sustainable Materials Institute (2001)	2	5	2	1	1	1	1	13	1.9	
Manufacturing energy consumption - asphalt	Canadian Industry Program for Energy Conservation (2005)	1	5	4	3	4	1	1	19	2.7	Y
Recycling Emissions	Levis (2008)	4	5	1	1	1	4	1	17	2.4	
Asphalt Shingles	**Average Score**	**4**	**5**	**2**	**2**	**2**	**4**	**2**	**20**	**2.8**	**2.8**
Manufacturing - virgin production	Athena Sustainable Materials Institute (2000)	2	5	3	1	1	2	1	15	2.1	Y
Composition, Recycling, and Combustion of shingles	CMRA (2007)	4	5	1	2	5	5	5	27	3.9	Y
Recycling Emissions	Cochran (2006)	4	5	1	1	1	4	1	17	2.4	
Recycling loss rate	Berenyi (2007)	4	5	1	2	1	4	1	18	2.6	
Carpet	**Average Score**	**3**	**5**	**3**	**3**	**3**	**4**	**3**	**26**	**3.7**	**3.4**
Fuel mix, energy use in manufacturing	FAL (2002)	4	5	1	2	5	2	5	24	3.4	Y
Process emissions, fuel mix	EPA (2003)	2	5	1	1	1	4	1	15	2.1	Y
Process and transportation emissions	Plastics Europe (2005a)	1	5	4	4	5	4	5	28	4.0	
Process and transportation emissions	Plastics Europe (2005b)	1	5	4	4	5	4	5	28	4.0	
Material composition, Recycling	Realff (2011)	5	4	5	5	5	5	5	34	4.9	
Clay Bricks	**Average Score**	**2**	**4**	**2**	**1**	**1**	**1**	**1**	**11**	**1.6**	**1.6**

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	**Reference**	**Data generation method & verification**	**Data year**	**Region of data**	**Technology type, scale**	**Representativeness, sample size**	**Third party or internal reviewer(s)**	**% of flows covered**			
Process and transportation emissions	Athena (1998)	2	5	3	1	1	1	1	14	2.0	Y
Process and transportation emissions	EPA (2018b)	1	2	1	1	1	1	1	8	1.1	Y
Concrete	**Average Score**	**1**	**5**	**1**	**3**	**1**	**4**	**1**	**16**	**2.2**	**2.2**
Process and transportation emissions - virgin	EPA (2003)	1	5	1	2	1	4	1	15	2.1	Y
Process and transportation emissions - recycled	Wilburn and Goonan (1998)	1	5	1	3	1	4	1	16	2.3	
Dimensional Lumber	**Average Score**	**2**	**4**	**2**	**2**	**1**	**1**	**1**	**12**	**1.7**	**1.7**
Cradle to gate GHG emissions for new and recycled	Bergman et al. (2013)	2	4	1	2	1	1	1	12	1.7	Y
Cradle to gate GHG emissions for new	American Wood Council (2013)	2	4	2	1	1	1	1	12	1.7	
Drywall	**Average Score**	**2**	**5**	**2**	**2**	**1**	**2**	**2**	**16**	**2.2**	**2.1**
Manufacturing, fuel mix, transportation	Venta (1997)	2	5	3	1	1	1	1	14	2.0	Y
Moisture content and carbon storage factor	Staley and Barlaz (2009)	2	4	1	1	1	1	1	11	1.6	
Process emissions and fuel mix	FAL (2007)	2	5	1	1	1	1	1	12	1.7	Y
Composition of recycled drywall	WRAP (2008)	2	5	4	3	1	5	1	21	3.0	
Transportation Energy	BTS (2013)	3	4	2	2	2	4	5	22	3.1	
Transportation Energy - recycled drywall	U.S. Census Bureau (2004)	1	5	1	1	1	1	1	11	1.6	
Fiberglass Insulation	**Average Score**	**3**	**5**	**3**	**2**	**2**	**3**	**2**	**20**	**2.8**	**3.1**
Sourcing raw material - sand	Athena Sustainable Materials Institute (2000)	2	5	4	1	1	2	1	16	2.3	
Sourcing raw material - soda ash and limestone	NREL (2009)	2	5	1	1	1	4	1	15	2.1	

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	Reference	Data generation method & verification	Data year	Region of data	Technology type, scale	Representativeness, sample size	Third party or internal reviewer(s)	% of flows covered			
Glass Recycling & Transport emissions	Enviros Consulting (2003)	2	5	4	2	1	4	1	19	2.7	
Transportation Energy	BTS (2013)	3	4	2	2	2	4	5	22	3.1	
Manufacturing process and emissions	Miller (2010)	5	4	5	5	5	5	5	34	4.9	
Manufacturing process and emissions	Lippiatt (2007)	2	5	1	1	1	1	1	12	1.7	Y
Fly Ash	**Average Score**	**2**	**5**	**1**	**1**	**1**	**4**	**1**	**15**	**2.1**	**2.1**
Recycling emissions	EPA (2003)	2	5	1	1	1	4	1	15	2.1	Y
Medium-density Fiberboard	**Average Score**	**2**	**3**	**2**	**1**	**1**	**1**	**1**	**11**	**1.5**	**1.5**
Manufacturing and transportation	Wilson (2010)	2	4	1	1	1	1	1	11	1.6	Y
Manufacturing - virgin inputs	Composite Panel Association (2018	2	2	2	1	1	1	1	10	1.4	
Structural Steel	**Average Score**	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**14**	**2.0**	**1.9**
Transportation emissions	BTS (2013)	3	4	2	2	2	4	5	22	3.1	
Transportation emissions	EPA (1998)	2	5	1	1	3	2	1	15	2.1	
Composition of structural steel - virgin inputs	U.S. Department of Commerce (2020)	1	2	1	2	1	4	1	12	1.7	
Composition of structural steel - virgin inputs	World Steel Association (2020)	2	2	4	2	1	1	1	13	1.9	
manufacturing and transportation emissions - virgin inputs	AISI (2017)	1	3	4	1	1	1	1	12	1.7	Y
Process emissions; manufacturing - recycled inputs	AISI (2016)	2	3	1	1	1	1	1	10	1.4	Y
Vinyl Flooring	**Average Score**	**2**	**5**	**3**	**2**	**2**	**3**	**2**	**19**	**2.7**	**2.9**
Transportation emissions	ECOBILAN (2001)	2	5	4	1	2	4	1	19	2.7	
Manufacturing process and emissions	Jones (1999)	3	5	5	3	5	4	5	30	4.3	
VCT life cycle emissions	Lippiatt (2007)	2	5	1	1	1	1	1	12	1.7	Y
Composition of vinyl flooring	Baitz et al. (2004)	2	5	4	3	1	1	1	17	2.4	Y

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	Reference	Data generation method & verification	Data year	Region of data	Technology type, scale	Representativeness, sample size	Third party or internal reviewer(s)	% of flows covered			
Manufacturing process and emissions	FAL (2007)	2	5	1	1	1	1	1	12	1.7	
Transportation Energy	BTS (2013)	3	4	2	2	2	4	5	22	3.1	
Wood Flooring	**Average Score**	**2**	**5**	**2**	**2**	**2**	**2**	**2**	**16**	**2.3**	**2.3**
Cradle to gate GHG emissions for new and recycled	Berman et al. (2013)	2	4	1	2	1	1	1	12	1.7	
Manufacturing - virgin inputs	American Wood Council (2013)	2	4	2	1	1	1	1	12	1.7	
Transportation Energy	BTS (2013)	3	4	2	2	2	4	5	22	3.1	
Manufacturing material consumption	Bergman and Bowe (2008)	2	5	1	2	4	1	1	16	2.3	Y
Manufacturing and transportation	Hubbard and Bowe (2008)	2	5	2	2	4	2	1	18	2.6	Y
Harvesting wood - energy use	Athena Sustainable Materials Institute (2000)	2	5	4	1	1	2	1	16	2.3	Y
Tires	**Average Score**	**3**	**5**	**2**	**2**	**3**	**4**	**2**	**21**	**3.0**	**3.0**
Scrap tire end-of-life usage	RMA (2009a)	4	4	1	1	1	5	1	17	2.4	Y
Process energy requirements for a new tire	Atech Group (2001)	4	5	3	2	1	3	1	19	2.7	Y
Tire energy content for combustion	CIWMB (1992)	2	5	2	1	5	5	1	21	3.0	
Retention rate and energy required for pulverization process (method of recycling)	Corti and Lombardi (2004)	3	5	3	1	5	2	1	20	2.9	
Fuel consumption for virgin tires	EIA (2009)	2	5	1	1	1	5	1	16	2.3	
Assumptions for composition, uses, and energy of scrap tires	EPA (1998)	2	5	1	1	3	2	1	15	2.1	
Transportation energy requirements	FAL (1994)	2	5	1	1	2	1	1	13	1.9	
Scrap tire life cycle emissions	ICF (2006)	4	5	3	1	5	5	1	24	3.4	

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	Reference	Data generation method & verification	Data year	Region of data	Technology type, scale	Representativeness, sample size	Third party or internal reviewer(s)	% of flows covered			
Method for retreading tires (used in documentation chapter)	Nevada Automotive Test Center (2004)	5	5	1	1	5	5	1	23	3.3	
Composition of fiber in tires	NIST (1997)	5	5	1	1	5	5	1	23	3.3	
Offset energy from sand in rubber	Venta and Nisbet (2000)	2	5	4	1	1	2	1	16	2.3	
Tire manufacturing energy	RMA (2010a)	5	4	5	5	5	5	5	34	4.9	
Industry average scrap tire recovery rate	RMA (2010b)	5	4	5	5	5	5	5	34	4.9	
Cryogenic grinding process (used in documentation chapter)	Praxair (2009)	5	4	5	5	5	5	5	34	4.9	
Retail transport requirements	NREL (2015)	1	3	1	1	1	2	1	10	1.4	
Synthetic rubber manufacturing and transportation	Pimentel et al. (2002)	4	5	1	1	1	5	5	22	3.1	
Scrap tire average weight	RMA (2009b)	2	4	1	1	1	5	1	15	2.1	
Retail transport requirements	BTS (2013)	3	4	2	2	2	4	5	22	3.1	
Food Waste	**Average Score**	**1.8**	**4.1**	**2.1**	**1.2**	**2.1**	**2.5**	**1.1**	**15**	**2.1**	**2.1**
Beef	**Average Score**	**2**	**3**	**1**	**1**	**1**	**4**	**1**	**13**	**1.9**	**1.9**
Cradle to packing plant emission and energy factors for beef production	Battagliese (2014)	2	3	1	1	1	4	1	13	1.9	Y
Cradle to packing plant emission and energy factors for beef production	Battagliese et al. (2013)	2	3	1	1	1	4	1	13	1.9	Y
Poultry	**Average Score**	**2**	**4**	**1**	**1**	**2**	**3**	**1**	**14**	**2.0**	**2.0**
Cradle to farm energy and emission factors for poultry	Pelletier (2008)	2	4	1	1	3	3	1	15	2.1	Y
Cradle to farm energy and emission factors for poultry	Pelletier (2010)	2	4	1	1	1	3	1	13	1.9	Y
Grains and Bread	**Average Score**	**1**	**4**	**4**	**1**	**3**	**1**	**1**	**16**	**2.3**	**2.3**
LCI data for grain drying	Nemecek and Kagi (2007)	2	4	5	1	4	1	1	18	2.6	

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
			Temporal correlation	Geographical correlation	Technological correlation	Data collection methods					
Unit process(es)	**Reference**	**Data generation method & verification**	**Data year**	**Region of data**	**Technology type, scale**	**Representativeness, sample size**	**Third party or internal reviewer(s)**	**% of flows covered**			
Process emissions from bread production	Espinoza-Orias et al. (2011)	1	4	5	1	4	1	1	17	2.4	Y
U.S. grains supply data	USDA (2012a)	1	5	1	2	2	1	2	14	2.0	Y
Fruits and Vegetables	**Average Score**	**2**	**4**	**2**	**1**	**2**	**5**	**2**	**19**	**2.7**	**2.7**
Energy impacts of produce transportation	Bernatz (2009)	2	5	1	1	1	5	1	16	2.3	
Cradle to farm GHG emissions for fruits and vegetables	Venkat (2012)	2	4	1	1	1	5	1	15	2.1	Y
Vegetables production data	Fake et al (2009)	3	4	2	1	3	5	3	215	3.0	Y
Orange production data	O'Connell et al. (2009)	3	4	2	1	3	5	3	21	3.0	Y
Tomato production data	Stoddard et al. (2007)	3	5	2	1	3	5	3	22	3.1	Y
Apple production data	Wunderlich et al. (2007)	3	5	3	1	4	5	4	25	3.6	Y
Banana production data	Luske (2010)	2	5	3	1	2	5	2	20	2.9	Y
Potato production data	Ecoinvent 2.0	1	3	4	1	1	1	1	12	1.7	Y
Dairy Products	**Average Score**	**3**	**4**	**1**	**2**	**1**	**2**	**1**	**13**	**1.9**	**1.8**
Process emissions from milk production	Thoma et al. (2010)	3	4	1	1	1	1	1	12	1.7	Y
U.S. dairy supply data	USDA (2012b)	2	4	1	2	1	3	1	14	2.0	
Yard Trimmings	**Average Score**	**2**	**4**	**1**	**1**	**1**	**3**	**1**	**13**	**1.7**	**1.6**
Transportation emissions	FAL (1994)	2	5	1	1	2	1	1	13	1.9	
Carbon storage data	Barlaz (1998)	1	5	1	1	1	3	1	13	1.9	Y
Process emissions and energy consumption	Hodge et al. (2016)	2	3	1	3	2	1	1	13	1.9	Y
U.S. yard trimmings generation and treatment data	EPA (2018a)	2	3	1	1	1	4	1	13	1.9	
Landfill gas collection efficiency modeling	Levis and Barlaz (2014)	2	3	1	1	1	5	1	14	2.0	
Process emissions and energy consumption	EPA (2006)	2	5	1	1	2	4	1	16	2.3	Y

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
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Unit process(es)	Reference	Data generation method & verification	Data year	Region of data	Technology type, scale	Representativeness, sample size	Third party or internal reviewer(s)	% of flows covered			
N_2O values for yard trimmings combustion	IPCC (2006)	1	5	3	1	1	1	1	13	1.9	Y
Landfilling	**Average Score**	**2**	**4**	**1**	**2**	**1**	**2**	**1**	**14**	**2.0**	**2.1**
Landfill gas collection	Levis and Barlaz (2014)	4	3	1	1	1	5	1	16	2.3	Y
Landfill emissions - carbon	Levis et al. (2013)	2	4	1	1	1	1	1	11	1.6	Y
Landfill emissions	EPA (2018c)	1	2	1	4	1	5	5	19	2.7	
Aerobic decomposition & landfill emissions	Freed et al. (2004)	4	5	1	1	1	5	1	18	2.6	
Landfill emissions - CO2 and CH4	Bingemer and Crutzen (1987)	2	5	2	3	1	1	1	15	2.1	
Landfill emissions - VOCs	Eklund B et al. (1998)	1	5	1	2	5	1	1	16	2.3	
Landfill emissions - CH4, CO2, material decomposition	Barlaz (1998)	1	5	1	1	1	3	1	13	1.9	Y
Material decomposition	Wang, X et al. (2011)	2	4	1	1	1	1	1	11	1.6	Y
Material decomposition	Wang, X et al. (2013)	2	4	1	1	1	1	1	11	1.6	
Component-specific decay rates	De la Cruz and Barlaz (2010)	2	4	1	1	1	1	1	11	1.6	Y
Composting	**Average Score**	**2**	**4**	**2**	**2**	**2**	**1**	**1**	**14**	**2.0**	**2.0**
Composting Emissions - food waste	Oregon DEQ (2014)	2	5	4	1	1	1	1	15	2.1	Y
Fugitive emissions for compost waste	Williams et al. 2019	2	1	2	2	5	1	1	14	2.0	Y
Composition of Composting Waste Stream	EPA 2014	2	3	1	3	1	4	1	15	2.1	
Composting Emissions - GHGs	Amlinger et al. 2008	2	5	4	1	1	1	1	15	2.1	
Composting Emissions - yard waste	FAL (1994)	2	5	1	1	2	1	1	13	1.9	Y

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
		Flow Reliability	Flow representativeness				Process Review	Process Completeness			
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Unit process(es)	**Reference**	**Data generation method & verification**	**Data year**	**Region of data**	**Technology type, scale**	**Representativeness, sample size**	**Third party or internal reviewer(s)**	**% of flows covered**			
Food and yard waste emissions	NREL (2015)	2	3	1	5	1	1	1	14	2.0	Y
Carbon storage in soil	Beck-Friis et al. 2000	1	5	3	2	1	1	1	14	2.0	
Combustion	**Average Score**	**3.1**	**4.8**	**3.0**	**3.2**	**3.4**	**3.9**	**2.8**	**24**	**3.4**	**3.1**
Non-biogenic share of carbon in textiles	DeZan (2000)	5	5	5	5	5	5	5	35	5.0	
Percentage of textile discards combusted in U.S.; non-biogenic carbon content plastic, textiles, rubber and leather	Van Haaren et al. (2008)	1	5	1	2	1	5	1	16	2.3	Y
Transportation emissions	FAL (1994)	2	5	1	1	2	1	1	13	1.9	
Transportation emissions	NREL (2015)	1	3	1	1	1	2	1	10	1.4	
Carpet and tires combustion energy content	Realff (2010)	3	4	1	3	5	5	5	26	3.7	Y
Specific heat data of materials	Incropera and DeWitt (1990)	5	5	5	5	5	5	5	35	5.0	
Wood flooring combustion energy content	Bergman and Bowe (2008)	1	5	1	2	3	1	2	15	2.1	Y
Energy content of specific materials in MSW	Gaines and Stodolsky (1993)	2	5	1	2	5	5	1	15	3.0	Y
Energy content of specific materials in MSW	Procter and Redfern (1993)	2	5	5	2	3	3	1	21	3.0	Y
Combustion system efficiency of mass burn plants	Zannes (1997)	5	5	5	5	5	5	5	35	5.0	
Energy content of RDF; combustion system efficiency	Harrington (1997)	5	5	5	5	5	5	5	35	5.0	
Combustion system efficiency of RDF plants	IWSA (2000)	5	5	5	5	5	5	5	35	5.0	
Energy content of mixed MSW combusted; losses in transmission and distribution of electricity specific to WTE combustion facilities.	IWSA and American Ref-Fuel (1997)	5	5	5	5	5	5	5	35	5.0	

Dataset	Data Source	Flow Indicators					Process Indicators		Total Score	Average Score	Weighted Average Score and Key Sources (Y)
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Unit process(es)	Reference	Data generation method & verification	Data year	Region of data	Technology type, scale	Representativeness, sample size	Third party or internal reviewer(s)	% of flows covered			
Energy content of RDF; combustion system efficiency of RDF plants	NREL (1992)	1	5	1	2	1	5	1	16	2.3	Y
Amount of steel and ferrous metal recovered from mixed MSW combustion	Bahor (2010)	4	4	1	4	1	5	1	20	2.9	
Dimensional lumber and fiberboard energy content	Fons et al. (1962)	2	5	1	2	4	3	2	19	2.7	Y
Combustion emissions	IPCC (2007)	1	5	3	1	1	1	1	13	1.9	Y
Anaerobic Digestion	**Average Score**	**1.4**	**4.3**	**3.3**	**1.4**	**1.9**	**3.6**	**1.3**	**17.1**	**2.4**	**2.1**
N_2O and CH_4 emissions from compost heaps	Beck-Friis et al. (2000)	1	5	5	2	5	5	3	26	3.7	Y
GHG reductions as well as environmental and energy benefits from an LFG energy project	EPA (2013)	2	4	1	1	1	5	1	15	2.1	Y
Process emissions	Moller et al. (2009)	2	4	5	2	3	2	1	19	2.7	Y
Transportation emissions	NREL (2015)	1	3	1	1	1	2	1	10	1.4	
Chemical composition of materials	Riber et al. (2009)	1	5	5	1	1	5	1	19	2.7	
Process emissions	Boldrin et al. (2011)	2	4	5	2	1	3	1	18	2.6	Y
Carbon storage	Barlaz (1998)	1	5	1	1	1	3	1	13	1.9	Y