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Preliminary Assessment of the Flow of Used Electronics in Selected States: Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin

Prepared by

U.S. Environmental Protection Agency
Office of Research and Development
Cincinnati, OH

and

RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709
TI Project Number 0213199.004.008.005

Office of Research and Development
National Risk Management Research Laboratory
Land Remediation and Pollution Control Division

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NOTICE/DISCLAIMER

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and conducted the research described herein under an approved Quality Assurance Project Plan (Quality Assurance Identification Number L-20925). This report has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Abbreviations and Acronyms

ADR	Annual District Report
CEA	Consumer Electronics Agency
CED	Covered electronic device
CEQ	White House Council on Environmental Quality
CRT	Cathode ray tube
EED	Eligible electronic device
EO	Executive Order
EOL	End-of-life
EPA	U.S. Environmental Protection Agency
eWFM	e-waste flow model
GDP	Gross domestic product
GSA	General Services Administration
IDC	International Data Corporation
IDEM	Indiana Department of Environmental Management
IEPA	Illinois Environmental Protection Agency
IL	Illinois
IN	Indiana
ITAD	Information technology asset disposition
K–12	kindergarten through twelfth grade
kg	Kilogram
LCD	Liquid-crystal display
LED	Light-emitting diode
MFA	Material flows analysis
MI	Michigan
MI DEQ	Michigan Department of Environmental Quality
MN	Minnesota
MPCA	Minnesota Pollution Control Agency
mt	Metric tons
N/A	Not applicable
NSES	<i>National Strategy for Electronics Stewardship</i>
OEM	Original equipment manufacturer
OH	Ohio
OLED	Organic light-emitting diode

PC	Personal computer
PDA	Personal digital assistant
RCRA	Responsible Conservation and Recovery Act
RERA	Responsible Electronics Recycling Act
RoHS	Restriction of Hazardous Substances
SOTF	Sales obsolescence and transboundary flows
StEP	Solving the e-waste problem
TVs	Televisions
WEEE	Waste Electrical and Electronic Equipment
WI	Wisconsin
WI DNR	Wisconsin Department of Natural Resources

Executive Summary

Electronic waste (e-waste) is the largest growing municipal waste stream in the United States (GSA, 2015) with an estimated amount of 3.1 million short tons being generated in 2013 (EPA, 2015). The improper disposal of e-waste has environmental, economic, and social impacts, both domestically and internationally. Many of the devices that end up as e-waste contain recyclable components and valuable commodities such as plastics, glass, precious metals, and technology metals that can be used to manufacture new products. Environmentally, these valuable materials can offset the use of virgin materials in various manufacturing processes and potentially prevent environmental contamination if they are safely managed. Economically, recovery and recycling have important impacts through the creation of jobs and end markets for the materials of value. Socially, the impacts are mostly tied to the quality of life (e.g., human health) of individuals and communities when e-waste is exported to areas without mechanisms to safely and effectively manage and handle the waste. For these reasons, the need for proper end-of-life (EOL) management of these devices, which includes opportunities for beneficial use of materials, has become increasingly important to individual consumers, communities, policy makers, and manufacturers.

Increases in household income, coupled with rapid technology development and falling prices, have led to growth in the consumption of consumer electronics in the United States over the past two decades. The rapid growth in the consumer electronics markets and diversification in products manufactured has contributed to an equally rapid increase of obsolete equipment and devices ready for EOL management. Our increased reliance on electronic devices compels the need to take a long-term sustainable approach towards electronics stewardship across their life cycle.

In 2009, the White House established the Interagency Task Force on Electronics Stewardship. In 2011, this Task Force issued the *National Strategy for Electronics Stewardship* (NSES), which outlined a strategy for achieving the goals identified in President Barack Obama's 2009 Executive Order (EO) 13514, Federal Leadership in Environmental Energy and Economic Performance.¹ The national strategy is based on the following four goals: (1) building incentives for designing greener electronics and enhancing science,

¹ EO 13514 has been revoked by 2015 EO 13693, Planning for Federal Sustainability in the Next Decade. Although EO 13693 primarily sets specific goals for maintaining Federal Leadership in sustainability and greenhouse gas emission reductions over the next 10 years, it does not change the goals related to electronics stewardship established by EO 13514.

research, and technology development in the United States; (2) ensuring that the federal government leads by example; (3) increasing safe and effective management and handling of used electronics in the United States; and (4) reducing harm from U.S. exports of e-waste and improving handling of used electronics in developing countries (NSES, 2011 and 2014).

The U.S. Environmental Protection Agency's (EPA) Office of Research and Development, in support of Goals 3 and 4 of NSES has been working to improve our understanding of the quantity and flow of electronic devices from initial purchase to final disposition.

Understanding the pathways of used electronics from the consumer to their final disposition would provide insight to decision makers about their impacts and support efforts to encourage improvements in policy, technology, and beneficial use.

EPA's effort included three major activities. The first activity involved an evaluation of information on state e-waste legislation, financing mechanisms, implementation challenges, and available data related to collected and recycled quantities of covered electronic devices. The second activity involved a general search for existing data, methods, and tools for estimating the amount of electronic devices over their product life cycle. Through the first two activities, it was determined that a comprehensive and cost-effective mechanism was not available for tracking the flow and the reporting of used electronics and e-waste generation (coming out of use or post-use storage) and EOL management (domestically or elsewhere). The third activity is intended to address this information gap by developing a conceptual input-output model to assist information organization and analysis.

This report supports the EPA Office of Research and Development's efforts to understand the flows of used electronics and e-waste by reviewing the regulatory programs for the selected states and identifying the key lessons learned and best practices that have emerged since their inception. Additionally, a proof-of-concept e-waste flow model has been developed and is presented in this report. The model is intended to provide estimates of the quantity of e-waste generated annually at the national level, as well as for selected states. This report documents a preliminary assessment of available data and development of the model that can be used as a starting point to estimate domestic flows of used electronics from generation, to collection and reuse, to final disposition.

The model is designed to produce national-, regional-, and state-level data on the annual amount of electronic products entering EOL management. The electronics waste flow model can estimate the amount of electronic products entering the EOL management phase based on unit sales data in combination with estimates of years of useful life and average product

weights. The model estimates e-waste at the state level by using the gross domestic product as a proxy for the distribution of product sales across individual states.

The model predicted that the national-level estimate for the total e-waste amount has risen from 680,000 metric tons (mt) to more than 2.5 million mt over the past 20 years.

Comparing the 2013 estimates from the EPA study (2015) results, the current model estimates are 350,000 mt less, which could be attributed to updates made to product weights and lifetimes. The combined amount of e-waste estimated by the flow model to be entering EOL management for the six states evaluated here (i.e., Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin) represents approximately 11 percent of the nation's total amount in 2014 (or 318,000 mt). Additionally, based on the preliminary modeling results, the most notable contributions to new growth in the e-waste quantities ready for EOL management over the past 10 years are flat-panel personal computers (PCs), monitors, and flat-panel televisions. Portable PCs, which include laptops, are another growth category; however, the emphasis on size and portability for this product category has resulted in the relatively small contribution to total weight.

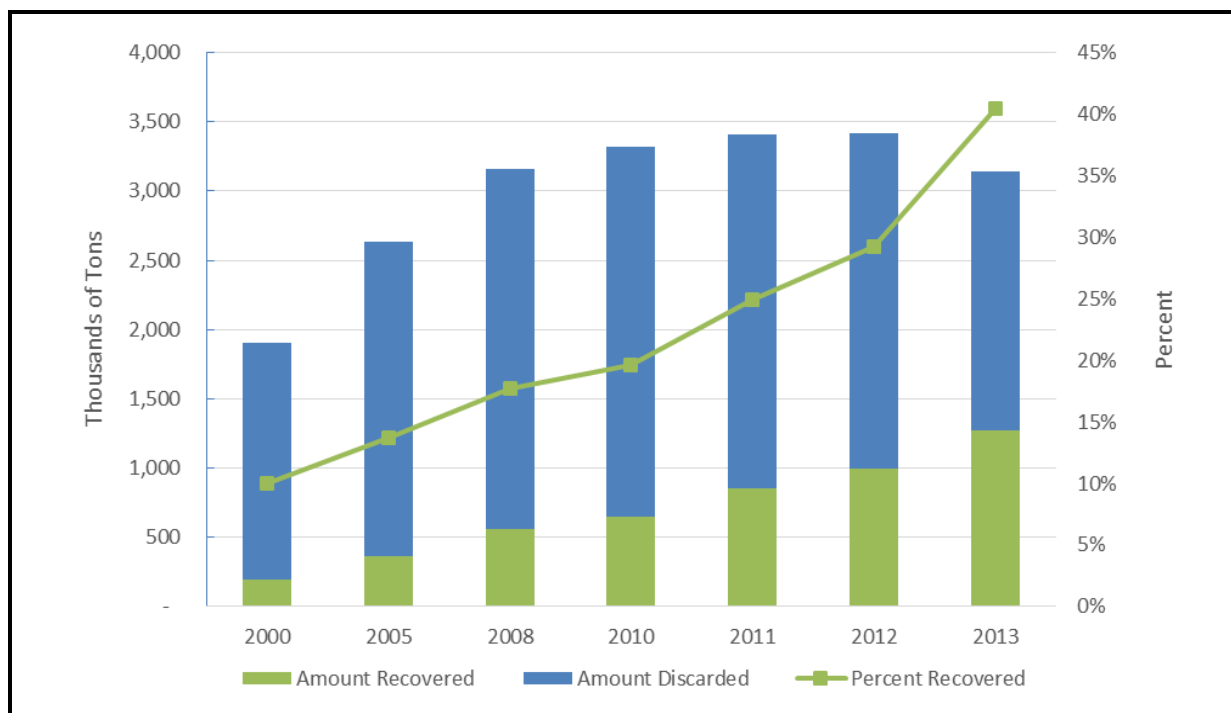
The study showed that although collection occurs within state boundaries, the recycling process involves the transboundary movement of used electronics. Depending on the scale of the recycling operation, the process could involve the receipt of used electronics across state lines for processing and could be preprocessed; disassembled components could be sold to a tertiary processor in another location. It is important to note that because of the dynamic nature of the recycling industry and the commodities markets, the flow of e-waste may frequently change, which requires flexible and adaptable flow tracking. The current proof-of-concept version of the e-waste flow model provides national, regional, and state-level e-waste estimates. These estimates are intended to assist the key stakeholders in their understanding of electronic material flows. However, there are several recommended next steps that are critical to continued refinement of the model. These next steps can be categorized into three areas that include improved functionality, calibration using other data sets, and the development of modules for evaluating transport of e-waste flows across state and national boundaries. Completing these steps will enhance the characterization of e-waste flows in terms of location, final disposition to landfills and incinerators, and utilization in new products.

1. INTRODUCTION

Electronic waste (e-waste)² is the fastest growing waste stream in the United States (GSA, 2015). Although the specific number and types of products vary significantly from person to person and business to business, our reliance on electronic technology is not going away, and neither are the products themselves. The U.S. Environmental Protection Agency (EPA) estimates that 3.1 million tons of consumer e-waste were generated in 2013, rising steadily from 1.9 million tons produced in 2000 (EPA, 2015). Ongoing technological advancements, and in some cases, the reduction in price, are shortening the life span of many electronic products, contributing to the rise of e-waste generation in the United States. Although the rate of recovery among selected consumer electronics continues to increase, today averaging approximately 40 percent, the total amount of discarded consumer electronics is also rising (Figure 1-1). In 2013, more than 1.8 million tons of selected consumer electronics were discarded, ending up in landfills or incinerators (EPA, 2015a). The rate of selected consumer electronics recovery was approximately 40 percent in 2013 (1.27 million tons), which equates to approximately 8 pounds per person per year recovered in 2013 (EPA, 2015).

The improper management of e-waste has environmental, economic, and social impacts domestically and internationally. Electronic components may contain heavy metals such as lead, mercury, cadmium, hexavalent chromium (Khaliq et al., 2014; Pinto, 2008; Shuey and Taylor, 2004; Iji and Yokoyama, 1997; Ewasteguide.info, 1996), useful precious and rare earth metals. Recovering and reusing these valuable materials can offset the use of virgin materials in various manufacturing processes and potentially prevent environmental contamination if they are safely managed (disposed of in a lined landfill with leachate collection, or incinerated with the proper emission controls). Economically, recovery and recycling have important impacts through the creation of jobs and end markets for the materials of value. Social impacts are mostly tied to the quality of life (e.g., human health) of individuals and communities that are affected by the improper export of e-waste to areas without mechanisms to safely and effectively manage and handle the waste (e.g., developing countries).

² The term “e-waste” is used generically throughout this report to refer to discarded electronic devices and related materials and components that are ready for end-of-life management.

Figure 1-1. Total Consumer Electronics Recovered and Discarded Between 2000 and 2013

Sources: EPA, 2015; EPA, 2014.

Note: Amount Recovered relates to the tonnage collected for recycling or reuse. Amount Discarded refers to the amount going to municipal solid waste landfills or waste incinerators.

With respect to used electronics, the main federal law governing solid waste, the Resource Conservation and Recovery Act (RCRA), only addresses cathode ray tubes (CRTs). Individual state regulations may differ by product coverage and may ban all exports of used electronics or e-waste from the United States. Used electronics, which are sold for to a secondary owner, and e-waste may be exported directly from the United States to developing countries, or it can be exported to an intermediate country that may then re-export the product. The movement of used electronics or e-waste across national boundaries can happen legally, or illegally.³ Regardless of whether the products are moved legally or illegally, a comprehensive and cost-effective mechanism for tracking and reporting used electronics and e-waste from generation in the United States to end-of-life (EOL) management (domestically or elsewhere) is not available. Understanding the pathways of

³ In 2013, the Responsible Electronics Recycling Act (RERA) was introduced to the 113th Congress (HR 2791, <https://www.congress.gov/113/bills/hr2791/BILLS-113hr2791ih.xml>). RERA would have made it illegal to export e-waste from the United States to developing nations. The Bill received bipartisan support, but it was not passed and was not reintroduced to the 114th Congress.

used electronics from the consumer to their final disposition would provide insight to decision makers about these impacts and support efforts to encourage improvements in policy, technology, and beneficial use.

1.1 Report Objectives and Scope

In 2009, Executive Order (EO) 13514, Federal Leadership in Environmental, Energy, and Economic Performance, called for federal agencies to promote electronics stewardship. The Interagency Task Force on Electronics Stewardship was established by the General Services Administration (GSA) to develop a National Strategy for Electronics Stewardship. This Task Force was co-chaired by the White House Council on Environmental Quality (CEQ), EPA, and GSA. In its current form, the Task Force is co-chaired by the Department of Energy (DOE), EPA, and GSA. An initial report was published in 2011, entitled the *National Strategy for Electronics Stewardship* (NSES; Interagency Task Force on Electronics Stewardship, 2011), a progress report in 2014 (Interagency Task Force on Electronics Stewardship, 2014), and an update on benchmarks in 2015 (Interagency Task Force on Electronics Stewardship, 2015).

Four goals are included in the NSES 2011 report:

- Goal 1—Build incentives for design of greener electronics, and enhance science, research, and technology development in the United States
- Goal 2—Ensure that the federal government leads by example
- Goal 3—Increase safe and effective management and handling of used electronics in the United States; and
- Goal 4—Reduce harm from U.S. exports of e-waste and improve safe handling of used electronics in developing countries.

The primary objectives of this report are to inform activities to achieve Goals 3 and 4 by:

- establishing an approach to gather, estimate, and provide public access to information on quantities and movement of used electronics within the United States; and
- developing a proof-of-concept method that in the future will allow the public and other key stakeholders to access information on quantities and flows of used electronics online.

This report documents a preliminary assessment of available data from a cluster of mid-West states and the development of a proof-of-concept method that can be used as a starting point to track domestic flows of used electronics from generation to collection and reuse to final disposition (i.e., recycling, landfilling, incineration, export). The states that were selected for initial analysis (i.e., Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin) were selected for several reasons. Most of these states codified their e-waste legislation in the early 2000s, all within 2 to 3 years of each other; for the five states with legislation (all except Ohio), the programs that are used to implement the laws are similar; and all of the states have a high level of coordination, cooperation, and sharing of information across the states; and they are in close geographic proximity.

The data presented in this report generally cover most types of used electronics and e-waste, but only aim to quantify and propose a methodology to track the four product categories presented in Table 1-1. These products are commonly included in state e-waste legislation and programs and are the most commonly used products in the United States (CTA, 2015). Tablets, although not specifically included in the scope of this report, and smartphones are the fastest growing consumer electronics segments. Emerging electronic devices, such as wearable fitness trackers, digital media streaming devices (e.g., Apple TV, Roku), and in-vehicle communication devices (e.g., navigation, back-up cameras, hands-free calling) are also growing in popularity. The Consumer Technology Association (CTA) expects these products to catch up with traditional electronics devices (e.g., TVs, DVD players, headphones) by 2018. As a result, they may be evaluated in future EPA efforts.

Table 1-1. Scope of Product Coverage Included in This Report

Product Category	Type	Description	Scope of Product Type^a
Televisions	CRT TVs	CRT or direct-view TVs	<ul style="list-style-type: none"> Includes digital direct-view CRT TVs, portable, table, and console, and CRT TV VCR/DVD combination products
	Flat screens	Thin, flat, non-CRT TVs other than projection TVs	<ul style="list-style-type: none"> Includes liquid-crystal displays (LCDs), plasma TVs, organic light-emitting diode TVs (OLED), and flat-panel TV combination products Does not include handheld TVs
Mobile phones	Mobile phones	Portable, handheld wireless telephones	<ul style="list-style-type: none"> Includes standard wireless telephones (i.e., cell phones) and smart phones Does not include portable MP3 and music players (e.g., iPods) that also allow for voice calling

(continued)

Table 1-1. Scope of Product Coverage Included in This Report (continued)

Product Category	Type	Description	Scope of Product Type^a
Computers	Desktop computers	Non-portable personal computers (PCs), excluding the external monitor	<ul style="list-style-type: none"> Includes brand name, or non-brand-name PCs assembled by vendors that purchase individual components Does not include mainframe computers, servers, or thin clients^b
	Portables	Portable, notebook, and laptop computers	<ul style="list-style-type: none"> Includes tablets, netbooks, ultra-compact laptops Does not include eBook readers, smartphones
Computer displays	CRT monitors	CRT monitors for use with PCs	<ul style="list-style-type: none"> Includes all PC CRT monitor types
	Flat-panel monitors	Flat-panel monitors for use with PCs	<ul style="list-style-type: none"> Includes all PC flat-panel types

^a Similar product definitions as those used in EPA (2011) are used here to maintain consistency across EPA efforts.

^b A thin client is a network computer that does not contain a hard drive disk. Thin clients connect over a network to a server where most of the data processing occurs (HP, 2009; EPA, 2011)

1.1 Conceptual Model of E-Waste Generation and Management

Generally speaking, consumers of electronic devices can be categorized as residential, commercial, governmental, or institutional. While these four consumer segments often purchase and use similar devices, the amount of each device used and how it is managed at the device's end of life can vary greatly between segments.

Residential consumers purchase electronics for personal use. The commonly disposed house-hold electronic devices in recent years are cell phones, laptops, and flat-screen televisions.

Commercial consumers are businesses and companies that provide goods or services. Most businesses acquire a large number of electronic devices such as laptops, desktop computers, and monitors to increase job efficiency and productivity.

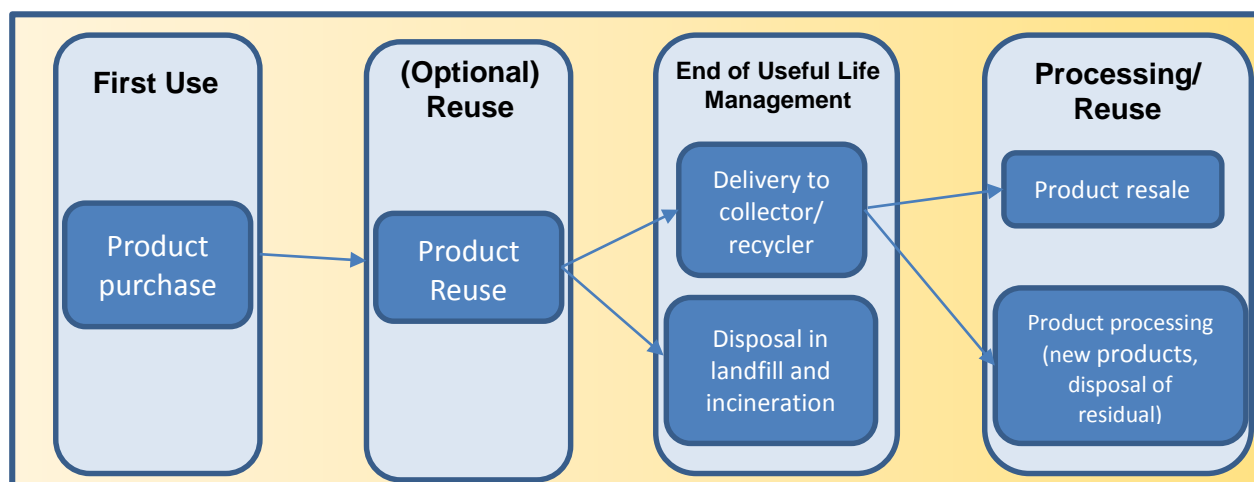
Governmental consumers consist of federal, state, and local government offices. Governmental consumers procure and use many of the same devices as commercial consumers (e.g., laptops, desktop computers, monitors); however, governmental consumers are often segmented into their own consumer group because of the many restrictions that direct how governmental employees must dispose of their electronics once they have reached their end of life. The Federal government, as a major consumer of

electronic devices, is using its purchasing power to shift to products with lower environmental impact across their life cycle.

Institutional consumers include colleges, universities, and other nonprofit organizations. Institutional consumers are unique because of their nonprofit status. Many nonprofit organizations are able to acquire electronic devices for a discounted rate or by donation. Colleges and universities may also have the ability to refurbish used electronics in-house, pushing the end of life of many devices out further. Since institutions have some of the same business needs as commercial consumers, devices such as desktop computers, laptops, and monitors are often procured and used; however, colleges and institutions may also see an increase in personal electronics (e.g., cell phones, laptops, tablets) due to their student population.

Despite the differences in behaviors across consumer segments, the electronic products themselves generally follow a common set of steps or phases in their life cycle. Constructing a general conceptual framework of the consumer electronic products' life cycle from purchase to final disposition aids in understanding the modeling approach and the design and implementation of existing legislative and voluntary programs to collect and recycle e-waste. This framework will serve as the basis for modeling the e-waste flows over time, which is described in detail in Section 3 of this report. Figure 1-2 presents the high-level conceptual framework of the four critical phases of product life cycle.

Figure 1-2. Framework for the Management of the End of Useful Life of Used Electronics



Products enter into this framework when they are purchased, then they are used, and eventually deemed to be at the end of their useful life for that consumer. If the electronic

device is generally in good condition or needs minimal repair to bring it to a good condition, it may be reused. This reuse may occur informally, for example, by passing a computer to a family member or donating the product to a school or charity. Reuse may also occur through more formal channels, like brokers or online marketplaces for used electronics. Parts of electronic devices, such as hard discs, are data-cleaned and sometimes reused.

Irrespective of the number of users, each product has an expected technical lifetime after which the device is no longer usable. Obsolescence may be due to component failure, cost prohibitive to repair, or incompatibility with newer technology including software or supporting devices. Once deemed unusable, electronics may be sent to, sorted by, and processed by a collector, recycler, or third party entity; disposed of in a landfill or incinerator; or stored in the owner's household or facility to be managed at a later date. Processing of used electronics may be partially or wholly completed domestically, while some integrated components may be exported for further processing internationally. Processed parts from the original device may be sold and reused in new products manufactured around the world. Residual scrap may then be sent to a landfill or incinerator.

1.2 Report Organization

This report is written at a general level to be accessible to readers with limited knowledge of used electronics and e-waste management and flows. Section 2 summarizes the existing programs and state legislation aimed at collecting e-waste for recycling in lieu of landfilling. Section 3 provides a brief summary of our findings from a review of the existing literature on alternative methods for conducting material flows analysis (MFA) and the data requirements for each approach. Section 3 also describes the enhanced version of EPA's e-waste flow model (eWFM), data, and assumptions, and presents national and regional results for selected states. The eWFM discussed in this report was enhanced with updated product weights and product lifetimes, which in turn improve the modeling and EOL management quantities of various electronics. Section 4 discusses key data gaps and limitations related to the eWFM, potential institutional and market changes that may impact the model and data inputs, and recommendations for next steps.

1.3 Quality Assurance and Data Limitations

This project involved collecting and analyzing secondary data and developing a proof-of-concept model. The model uses sales data in combination with time series data sets which provide average product weights and lifetimes. In addition, assumptions of market share across major consumer segments (i.e., residential, commercial, institutional, and

educational) have been made as noted in the report to allow for a demonstration of the proof-of-concept model. This work was conducted under an approved Quality Assurance Project Plan. The appropriateness of the data and their intended use were assessed with respect to the data source, the data collection timeframe, and the scale of the geographic area that the data represent. Preference was given to data that have undergone peer or public review (e.g., those published in government reports and peer-reviewed journals) over data sources that typically do not receive a review (e.g., conference proceedings, trade journal articles, personal estimates). However, where peer-reviewed data did not exist, parameters and modeling inputs were developed from the next highest quality available sources (e.g., grey literature, and product specification data sheets from manufacturers). Preference was given to more recent data over older data. In this report, the sources of all of the data and any identified limitations are presented.

2. E-WASTE FLOWS AND MANAGEMENT PROGRAMS

To date, 25 states have passed extended producer responsibility, consumer fee, or producer education laws that mandate e-waste recycling programs. Extended producer responsibility laws obligate manufacturers to facilitate and finance recycling of their EOL products. As an initial step, this study evaluated a cluster of states in the mid-West to understand the breadth of their e-waste programs. These states included Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin. Ohio has not codified any e-waste legislation to date, while the other five states in this cluster have (see Table 2-1). Because these laws were codified within a short time span of each other, the legislation and programs used to implement the laws are similar. This also means that the states did not have sufficient time to incorporate many lessons learned from implementing an e-waste program.

Table 2-1. E-waste Legislation and Implementing Programs in the Selected States

State	Name of Legislation	Date Codified	Effective Start Date	Program Name	Implementing Agency	Program Year Start and End Dates
IL	Electronic Products Recycling and Reuse Act	9/17/2008; amended 2011; 2015 ^a	1/1/2010	Electronic Waste Recycling	Illinois Environmental Protection Agency (IEPA)	January 1–December 31
IN	Indiana Electronic Waste Law	5/13/2009; amended in 2012	4/1/2010	Indiana E-Cycle	Indiana Department of Environmental Management (IDEM)	<i>Prior to 2012:</i> April 1–March 31 <i>2012 and on:</i> January 1–December 31
MI	Electronic Waste Takeback Program	12/29/2008	4/1/2010	Electronic Waste Takeback Program	Michigan Department of Environmental Quality (MI DEQ)	October 1–September 30
MN	Electronics Recycling Act	5/8/2007; amended in 2009, 2011, and 2015 ^b	8/1/2007	Product Stewardship Initiative for Electronics	Minnesota Pollution Control Agency (MPCA)	July 1–June 30
OH	No legislation					
WI	2009 Wisconsin Act 50	10/23/2009	1/1/2010	Wisconsin E-Cycle	Wisconsin Department of Natural Resources (WI DNR)	July 1–June 30

^a The 2015 amendments to the Illinois law included numerous changes (see IEPA, 2015b).

^b The 2015 amendments to the Minnesota law included several modifications (see 2015 Minnesota Session Laws, <https://www.revisor.mn.gov/laws/?year=2015&type=1&doctype=Chapter&id=4#laws.4.106.0>).

The information presented in this section is summary level and subject to change as each legislative session opens the opportunity for amendments. For example, Illinois and

Minnesota amended their e-waste laws in July 2015. Additional details on the e-waste programs for each of the states in the cluster evaluated in this report are provided in Appendix A. Details include the specific electronics covered, program registration, funding mechanisms, and a summary of how the manufacturer recycling goals are created.

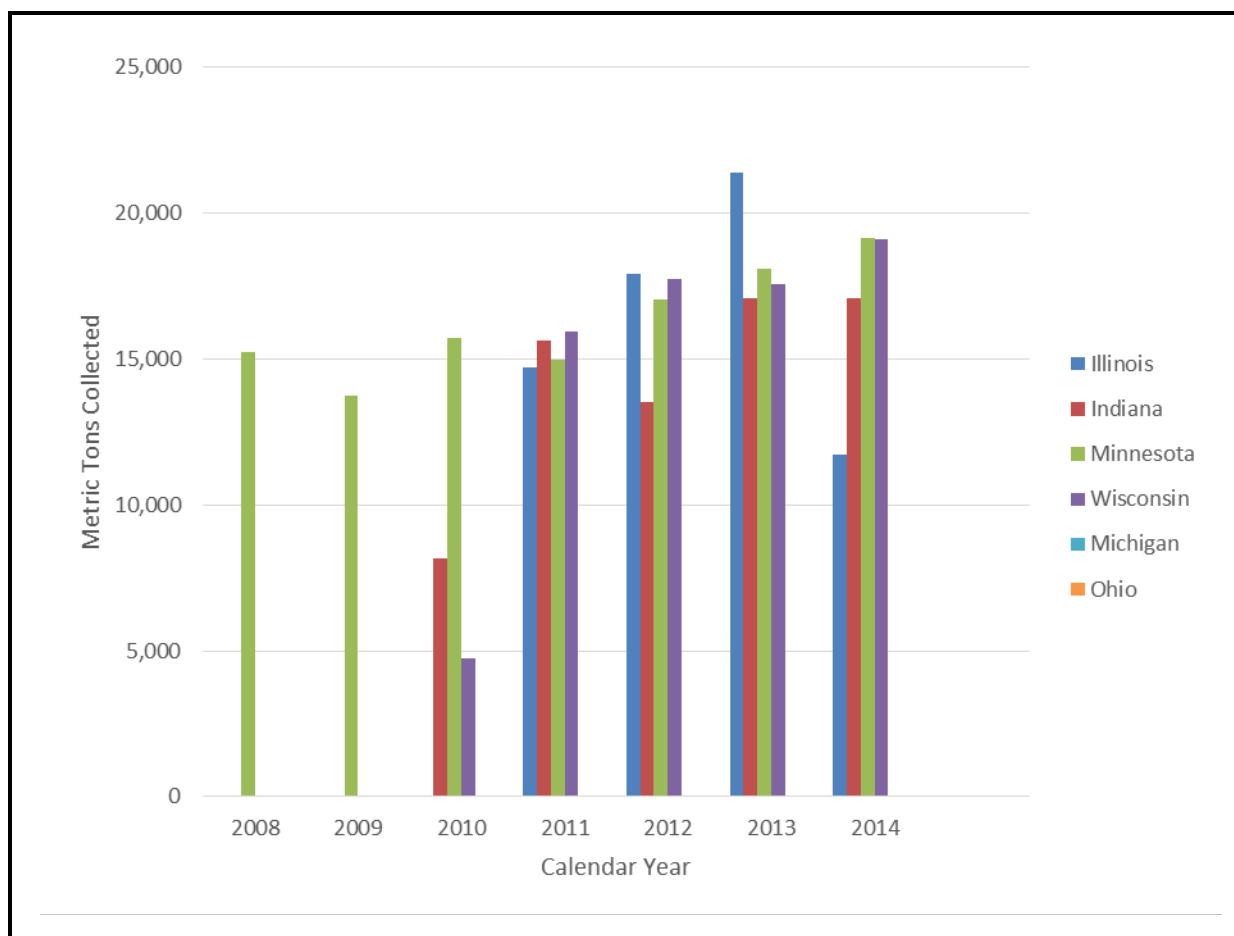
2.1 Collection Trends and Data Availability

Each state, regardless of whether legislation is in place, collects selected used electronics at low or no cost to residential consumers. Each of the selected states tracks weights of collected, covered or eligible electronic devices (CEDs and EEDs) to some extent. States with legislation require manufacturers, collection sites, or both to record and report these weights to the relevant state agency, whereas states without legislation may only track collection events or certain collection sites. Data are available through the relevant state agencies and may be published online on an annual basis, but by no means represent all used electronics in the respective state. For example, commercial businesses in the information technology asset disposition (ITAD) sector may track and manage most of the remaining portion but are not covered under state legislation. Many original electronics manufacturers (OEM) have take-back operations as part of their product stewardship programs.

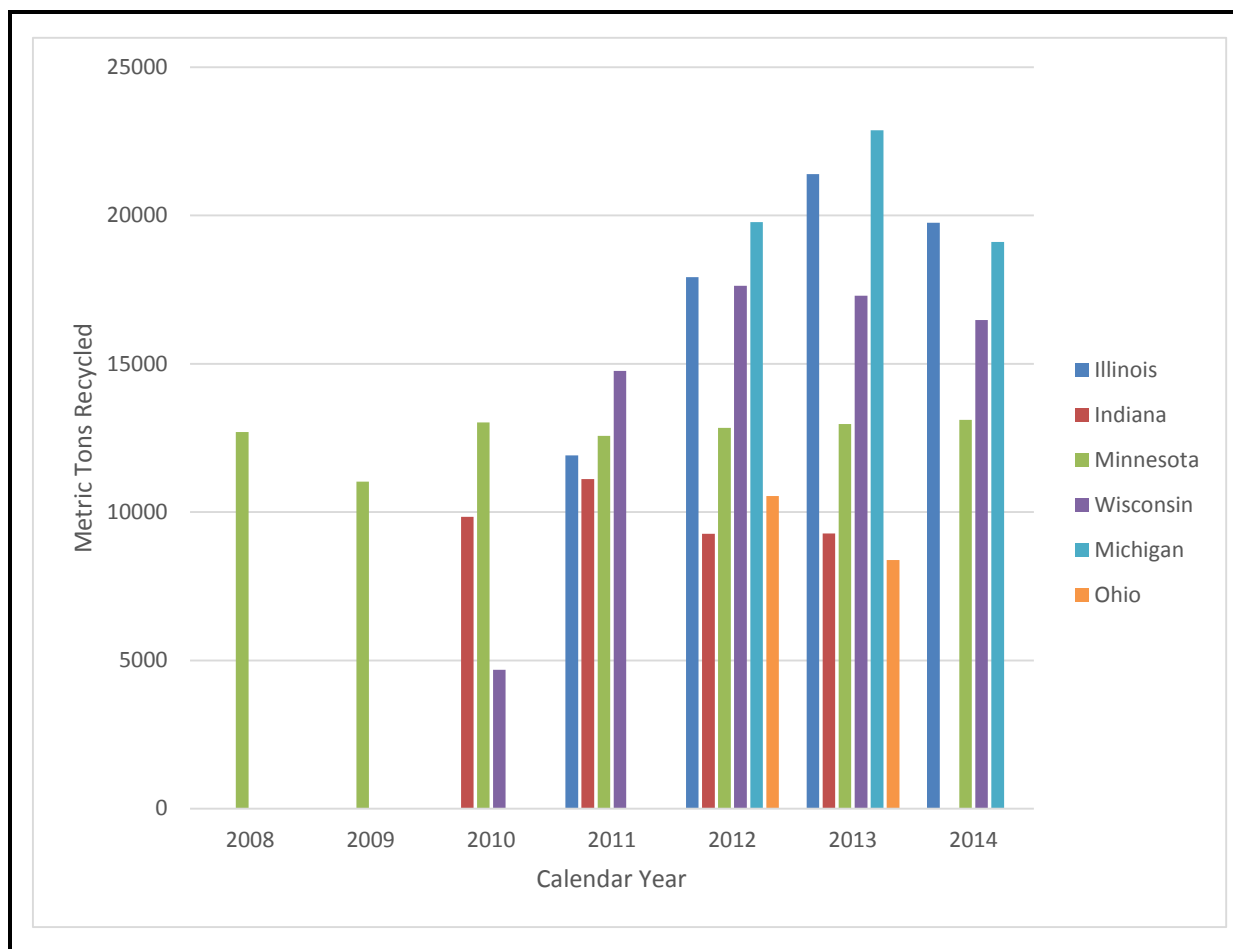
The state-reported actual weight of CEDs and EEDs collected and recycled are presented in Figures 2-1 and 2-2 for program years that ended in 2014. Actual weights are those exclusive of rural credits and reuse credits that the registered entities claim in their annual reports under the state legislation. Rural and reuse credits function (in the state programs) as an incentive to collect electronics in difficult to reach areas, while reuse credits offer an incentive to extend the product lifetime. These credits are multiplied by the weight collected that is from a rural area or reused. For example, if 1,000 tons of electronics were collected from a rural area, the 1,000 tons would be multiplied by a credit, say 1.5, such that the program weight becomes 1,500 tons. For simplicity, the years presented in these graphs are calendar years even though the program data do not correspond directly to calendar years (i.e., most states with legislation operate on a July to June program year). Data are not available for each state for each year because the effective start dates for the e-waste laws differ. Additionally, Michigan is not represented in Figure 2-2 because e-waste collection sites are not required to register under their program, thus these data are not available. For 2014, the actual weight collected and recycled in Indiana have not been aggregated and presented in a publicly available report as of the date of this report. For years 2012 and 2013, a state program report for Minnesota was not prepared and these

values have been interpolated using the 2011 (the last year of the program report) and 2014 data (using data provided by the state to the authors of this report). Collection data are not available for Ohio because this state does not track the quantity of electronics collected. Unlike the other selected states, Ohio does not have a landfill ban on electronics or e-waste legislation, thus there is no driver or specific mechanism for funding the costs associated with tracking electronics collection at the state level. Ohio does track a portion of the electronics recycled from collection events.

Figure 2-1. State-reported Actual Weight of CEDs and EEDs Collected Through 2014



Notes: Data were obtained from annual program reports and/or the state program coordinator (IDEM 2014; IEPA 2015a; IEPA 2014; IEPA 2013; MPCA 2010; MPCA 2011; WI DNR 2014). Data for MN were extrapolated for 2012 through 2014 because annual program data have not been published online as of the date of this report. Data are not available for all states and all years presented because either the state did not operate an e-waste program in that year (applies to Ohio) or data are not collected by the state (Michigan for all years). Data for Indiana in 2014 have not been published online as of the date of this report.

Figure 2-2. State-reported Actual Weight of CEDs and EEDs Recycled Through 2014

Notes: Data were obtained from annual program reports and/or the state program coordinator (IDEM 2014; IEPA 2015a; IEPA 2014; IEPA 2013; MI DEQ 2015; MPCA 2010; MPCA 2011; WI DNR 2014). Data for OH were provided by the state coordinator. Data for MN were extrapolated for 2012 through 2014 because annual program data have not been published online as of the date of this report. Data are not available for all years presented because the state did not operate an e-waste program in that year, data were not provided by the state (applies to Ohio), or an annual report is not publically available online as of the date of this report (Indiana for 2014). The quantities recycled for most states go beyond the CEDs/EEDs in the state programs.

While not complete across all years, these figures show that the actual weights collected and recycled vary by state. The year-to-year differences lie in the fact that the state programs are driven by program year goals, which are driven by manufacturer sales of CEDs in the previous year. Manufacturer sales are driven by supply and demand. Many states also have program years that do not follow a typical calendar year (e.g., July 1 of 1 year through June 30 of the following year). The effects of this mid-year program start date are evident for Wisconsin in Figure 2-1 because 2010 does not represent a true full calendar year of collection. As more communities, retailers, and manufacturers are beginning to

sponsor electronics takeback programs in various states, many of which are free to the consumer, the amount of electronic devices collected by is expected to grow. However, the new collection mechanisms could potentially reduce the amounts collected through the states E-Cycle programs.

2.2 Access to Collection and Recycling Sites

Electronics collection sites include permanent drop-off locations and temporary events (e.g., 1-day events at a specified location) that cater primarily to households. Collection and recycling sites are generally distributed across each state, with a larger number of sites in metropolitan areas because of the higher population density. Appendix A includes maps with locations of collectors and recyclers for each of the states in the cluster with e-waste legislation. The legislation in the selected states does not include siting requirements (e.g., one collection site for every 10,000 people) for collection sites like the requirements in other states (e.g., Washington, Oregon, New York). Several counties in each of the selected states do not have a collection site as presented in the state maps for collection and recycling sites in Appendix A. Recommendations from the Illinois Environmental Protection Agency (IEPA) to the Illinois Governor (IEPA, 2016) about their state program include a population density siting clause to reach both ends of the population density spectrum (very low to very high). Michigan does not require collection sites to register under their program, so information on the number and location of collection sites in Michigan is not readily available. The number of collection sites varies over each of the selected states' program years depending on the cost to maintain the site, frequency of use, current market prices, and the site's location (rural versus urban), which impacts how often haulers will come to the collection site to pick up material.

2.3 Costs of Manufacturer-Funded Collection

Covered entities under the state programs are required to register each year with the ruling body to monitor the activities of manufacturers, collectors, and recyclers and to track, validate, and enforce their goals under the directive of the selected states' e-waste programs. The states included in this evaluation prohibit manufacturers from selling their products, either directly or through a retailer, in their state if the manufacturer does not register with the program. Annual registration is required as opposed to a one-time registration process to more closely track trends in compliance and collection/recycling from year to year, which assists the ruling body of the program in evaluating what aspects of the program are working and which need improvement. Collection and recycling facilities in Ohio are not required to register with any state organization, and, while still impacted by

market fluctuations, they may be more naturally responsive to market forces of supply and demand compared to states with legislation.

Annual registration fees and penalty fees for not meeting annual program goals are collected from manufacturers to fund the e-waste programs implemented by the selected states. This cost model is referred to as extended producer responsibility. States may require a larger fee the first year followed by a lower annual fee each year thereafter. First-year manufacturer fees for the selected states range from \$2,500 to \$5,000 and subsequent annual fees range from \$1,250 to \$5,000. The annual registration fees are collected first, primarily to be used towards costs of administering the electronics recycling program within a given state. Some states allow the funds to be used for other purposes that benefit registrants and aid them in meeting their year-to-year targets. States may also use the program funds to provide grants for small businesses or rural areas to promote collection and recycling.

The trend in the reduction of the weight of electronic devices will continue to be an issue in the process of defining e-waste program goals and funding overall programs. Program goals are weight-based and correlated to the total weight of product sales in the previous year. Newer CEDs, however, tend to weigh less than older CEDs and the demand for recycling older CEDs will continue to grow as, presumably, manufacturer collection/recycling goals are based on lower weights (IDEM, 2014). Indiana, for example, considers it to be imperative to review the Indiana E-Waste Law on a regular basis (IDEM, 2014).

2.4 Outreach and Education (for Consumers and Manufacturers)

The extent of outreach and education for consumers and manufacturers varies by state and appears to be driven by the annual program budget and staff availability. Each state maintains a Web site dedicated to the disposition or reuse of electronics along with additional information on the location of collection and recycling sites. Of the selected sites, many appear to have provided a high-level of outreach and Wisconsin has held annual e-waste stakeholder workshops where staff from nearby state programs and other stakeholders can come to share their experiences and learn about new developments in technology, regulation and management options.

3. E-WASTE FLOW MODEL—A PROOF-OF-CONCEPT TOOL FOR ESTIMATING THE FLOW OF USED ELECTRONICS

3.1 Background of Materials Flows Analysis Methodologies

Material flow analysis (MFA) is a method used to understand and manage the flow of materials as they move from place to place within a defined geographic or temporal boundary. The results of an MFA are often used to support environmental and waste management decision making (Brunner and Rechberger, 2004; Kiddee et al., 2013). In the case of e-waste, where the materials move through several different consumers over a few years to a few decades, an MFA helps to understand the pathways and the intermediate and final destinations of the electronic devices and their components (if the components are destined for recycling). After the material flows are understood, consumers and decision makers can better manage the e-waste to promote beneficial use of the recyclable components and prevent potentially toxic materials from harming the environment and public health due to improper disposal or storage.

An MFA consists of the following components:

- system boundary (temporal, spatial, or both),
- processes (the number and type of processes to focus on),
- flows (how the products move from one process to another), and
- stocks (the quantity of products that flow through the system).

We reviewed the existing literature on current approaches to conducting an MFA and identified potential methods for calculating e-waste generation within the United States. Our first step was a search through ScienceDirect for English-language articles published since 2000. We also completed general Web searches using Google and focused searches of relevant Web sites, including those of the StEP (Solving the E-waste Problem) Initiative, the EPA, and the United Nations Environment Programme (UNEP). Selected details from the literature review are presented in Appendix B.

Through this review, we identified five methods based on the MFA concept: direct sales to e-waste, time step, market supply, consumption and use, and sales obsolescence and transboundary flows (Baldé et al., 2014; Duan et al., 2013; EPA, 2011; UNEP, 2007). Table 3-1 briefly describes each of these methods. Based on the existing literature, the sales obsolescence and transboundary flows (SOTF) method is the most complete method for

tracking the flow use electronics and e-waste. As such, SOTF is the method chosen for this analysis.

Table 3-1. Available MFA Methods to Assess E-Waste Flows

Method Name	Description
Direct Sales to E-Waste (UNEP, 2007)	A simplified methodology that assumes the quantity of e-waste generated in a given year is equivalent to the sales in that year. Assumes a saturated market and each sale of a new item is balanced by an item that is disposed of. (http://www.unep.or.jp/ietc/Publications/spc/EWasteManual_Vol1.pdf .)
Time Step (UNEP, 2007)	Private and industrial stock and sales data are used to calculate the quantity of e-waste generated. The e-waste potential during the collection phase at time t is calculated from the difference in stock levels of private and industrial equipment during the consumption phase in the period between two points in time (t and t-1), plus the sales in that period, minus the annual waste produced in that period up to time t-1. (http://www.unep.or.jp/ietc/Publications/spc/EWasteManual_Vol1.pdf .)
Market Supply (UNEP, 2007)	Relies on sales data and typical life spans of electronic devices. The waste potential during the collection phase at time t is calculated from sales data and information about consumption patterns. (http://www.unep.or.jp/ietc/Publications/spc/EWasteManual_Vol1.pdf .)
Consumption and Use (UNEP, 2007)	Estimates the amount of e-waste generated using stock and average life span data. The stock is the difference in products manufactured in a given year and the quantity of products sold in a given year; products that are stored in a given year are also included in the amount of stock. (http://www.unep.or.jp/ietc/Publications/spc/EWasteManual_Vol1.pdf .)
Sales Obsolescence and Transboundary Flows (Baldé et al., 2014; Duan et al., 2013; EPA, 2011; UNEP, 2007)	A variation of the market supply method that is used to calculate the amount of e-waste generated, but also considers reuse, recycling, exports, and disposal. Assumptions regarding product life spans (including reuse), recycling, storage, and disposal are used to reflect consumer behavior in the disposition of the products. (http://i.unu.edu/media/ias.unu.edu-en/news/7916/Global-E-waste-Monitor-2014-small.pdf . http://www.weee-share.eu/wp-content/uploads/2014/11/Quantitative-Characterisation-of-domestic-and-Transboundary-Flows-of-Used-Electronics.pdf . http://www.unep.or.jp/ietc/Publications/spc/EWasteManual_Vol1.pdf .)

Depending on the method chosen, various data are needed to estimate used electronics flows from first-time consumer use to EOL management. Before preparing an MFA, the scope of the products to be included should be defined, and then, whether specific product models will be defined. The minimum data requirements to model a scope of products are

- time period,
- region (e.g., city, state, country),

- type of consumer (e.g., residential, commercial, institutional),
- product sales,
- product weights (average or model-specific weights),
- product life spans (including reuse), and
- EOL management pathways (e.g., reuse, recycling, disposal, export).

The data should cover the same period and region. Additional data are required when considering transboundary flows and particularly exports.

3.2 E-Waste Flow Model Documentation

This section of the report introduces the proof-of-concept e-waste flow model (eWFM) developed for this study, which applies the SOTF method for tracking the flow of e-waste.

The eWFM employs a combination of top-down data sources and bottom-up assumptions to track the generation of e-waste by state and estimate the material flows from generation to collection. Examples of top-down data sources include national statistics on population, gross domestic product (GDP), and retail sales. Examples of bottom-up assumptions include average device weight per product based on the year of manufacturing, expected product lifetimes, and market share by consumer segment. Ultimately, in the future, our objective is to estimate material flows to the various disposition pathways (i.e., reuse, recycling, and disposal) and the quantities of e-waste processed domestically and internationally.

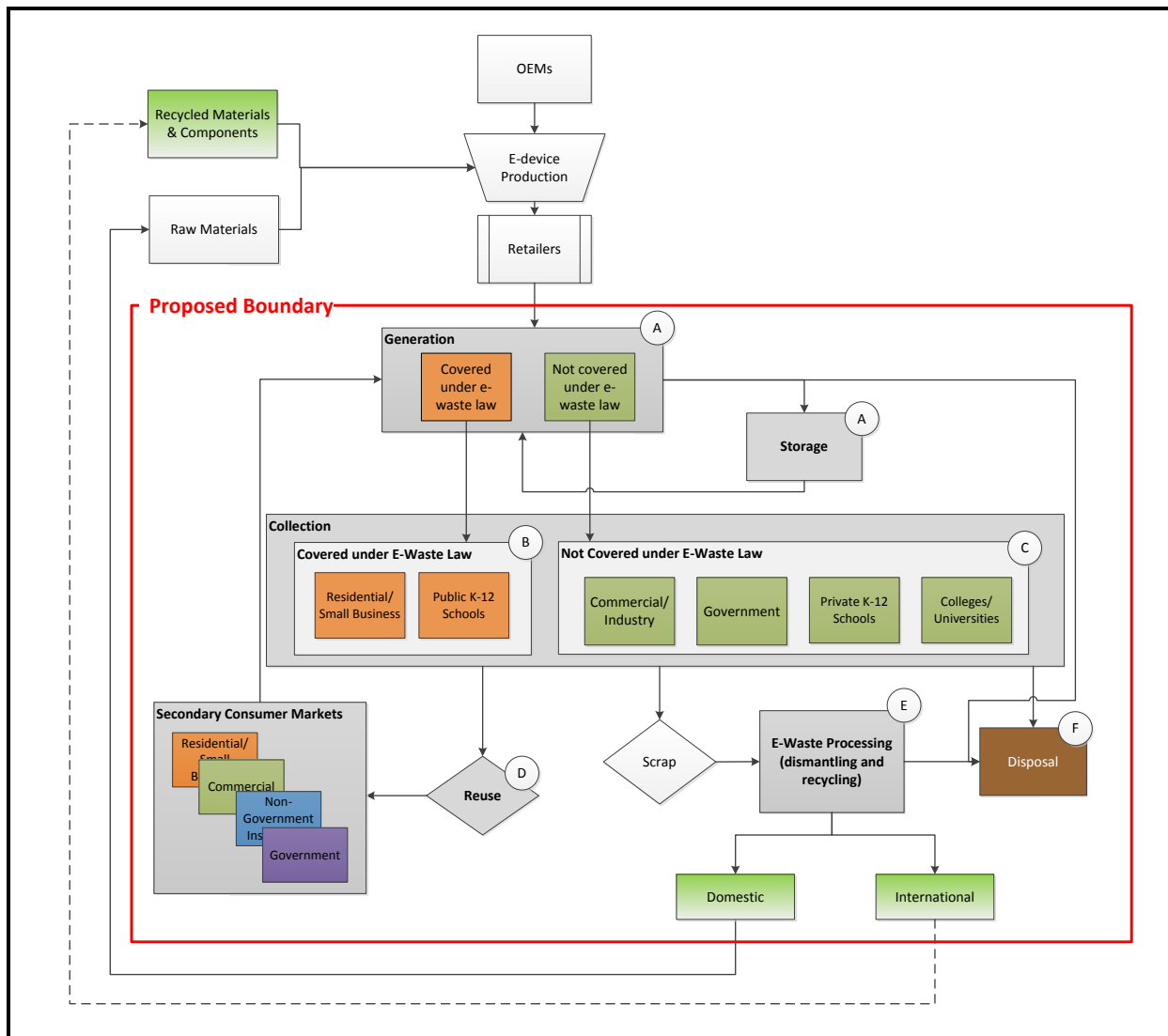
The eWFM is capable of producing national-, regional-, and state-level results regarding the amount of electronic products entering EOL management annually. Although the quality and availability of information on the markets and consumer behavior are improving, the rate of change in technology and market behavior is high. For this reason, the eWFM was designed to allow end users to update key parameters and data elements easily based on better information in the future. The model is intended to be a tool that supports end users such as policy makers and other key stakeholders with analyzing e-waste material flows.

3.3 Model Structure

The proof-of-concept eWFM currently estimates the annual amount of e-waste entering EOL management. Results include the number of units and corresponding tonnage by simulating the electronic product lifecycle. The model structure follows the general framework for e-waste generation presented in Section 1, Figure 1-2. Based on the information currently available from the cluster of states evaluated, the model was designed in a way that reflects

how recyclers collect information about used electronics and e-waste. Results from the model estimate the amount of used electronics, both in terms of mass and the number of units, entering the EOL management phase and then the final disposition (which is the combination of recycling, landfilling, and incineration). Reuse is factored into the product lifetime estimates in the model and as a result reuse is not modeled explicitly. The eWFM boundary begins when the product is purchased and ends with its final disposition, as illustrated in Figure 3-1.

Figure 3-1. Generic Materials Flow of Used Electronic Equipment



Within this boundary, the processes and flows are generally represented. Original equipment manufacturers (OEMs) make the products, which are sold to retailers, and then

purchased by consumers. Following product use, consumers generate e-waste and used electronics. After the material is generated, it flows to one of the following places: storage (e.g., a basement, attic, storage closet), disposal (e.g., landfill), or a collection (drop-off) center. Materials that are gathered through an e-waste collection program are sent to a processing (e.g., recycling) facility, are sent to another consumer for reuse, or are disposed of. Products that are reused will eventually go through the process of collection, recycling, reuse, or disposal. Materials collected for recycling will either be processed (dismantled, recycled) domestically or exported. Recycled materials (e.g., metals) may be used to manufacture a new or refurbished electronic device or another type of product, thus completing the cycle.

The model includes several data sources and assumptions that can be used to derive estimates of annual e-waste generation at the national, regional and state level. The current version of the proof-of-concept model is limited in scope to three major categories of consumer electronics: televisions, cell phones, and personal computers (PCs) and related products. Televisions are divided into five subcategories: color cathode ray tubes (CRTs) less than 19 inches, color CRTs greater than 19 inches, flat-panel TVs, color projection, and monochrome. PCs and related products include desktops, portables, hard copy peripherals (e.g., printers, scanners, fax machines), mice, keyboards, PC CRTs, and PC flat monitors.

3.4 Modeling Methodology

The model applies a sales obsolescence and transboundary flows method for estimating the amount of e-waste. This method is a variation of the market supply method that is used to calculate the amount of e-waste generated and that considers reuse, recycling, export, and disposal (landfilling). The annual e-waste generation is estimated from national sales data. Assumptions regarding product life spans (including reuse), recycling, storage, and disposal are used to reflect consumer behavior in the disposition of used electronic devices. This method is described by the UNEP (2007) as the Carnegie Mellon Method. Similar, but slightly more complex, methods are applied by Baldé et al. (2015) and Duan et al. (2013). The Carnegie Mellon Method is mathematically represented by Equation 1, as follows:

$$\text{e-waste (t)} = \sum_{i=0}^{t \leq T} \text{Sales}_t \cdot \left[\left(1 - e^{\left(\frac{T-t}{\beta} \right)^\alpha} \right) - \left(1 - e^{\left(\frac{(T-t)-1}{\beta} \right)^\alpha} \right) \right] \quad \text{EQ. 1}$$

Where:

- t = Year when the product was sold
- T = Year when e-waste was generated
- Sales_t = Industry sales for year t
- β = Weibull distribution scaling factor
- α = Weibull distribution shape factor.

The current model applies Weibull distributions to characterize product lifetimes. This is an improvement over the more common approach of discrete product lifetimes, in which a single value represents the average expected lifetime for each product (e.g., 20 years for a CRT TV). In contrast, the Weibull distribution is a continuous probability function that can be used to characterize product lifetime. The primary advantage of a Weibull distribution over a discrete product life span is the continuous nature of the distribution, which provides greater flexibility in characterizing the number of units entering EOL management each year. In other words, the Weibull distribution gives allowance for the possibility that electronic products may reach end-of-life after one year or may stay in use for many years, rather than assuming a fixed lifetime. This is why the eWFM was enhanced with the Weibull distribution for this analysis.

The Weibull distribution function is often used in reliability and survival analysis for estimating expected product lifetimes because of its versatility and simplicity. The two parameters that characterize the Weibull distribution are the scale (α) and shape (β). Both parameter values are always greater than zero. The scale parameter generally correlates with the life span with smaller values of the scale indicating shorter lifetimes. The shape parameter indicates the distribution of a life span; a small value equates to a larger spread in the life span of a product.

3.5 Data and Assumptions

The eWFM estimates the amount, both in mass and number of devices, for electronic products entering the EOL management phase annually. Estimates rely on unit sales data in combination with estimates of years of useful life and average product weight estimates. The model estimates e-waste at the state level using GDP per capita as a proxy for the distribution of product sales across individual states. The model currently includes four major consumer markets: residential, education, commercial, and institutional. Table 3-2 lists the data inputs and sources for each lettered process included in Figure 3-1 along with the data sources the eWFM uses.

Table 3-2. Data Requirements, Data Sources, and Potential Approaches to Fill Data Gaps in the Future

Stages of Material Flow ^a	Data Requirements	Data Source/Approach to Fill Data Gaps
Generation and Storage (A)	Sales data or market share by consumer segment (vintage from 1980–2014) Life span (years of first use, years or reuse)	▪ <u>Sales data</u> : Use the market sales data presented by EPA (2011) for products within the scope of this report. Conduct an Internet search for sales by product for 2010–2014 (not included in EPA, 2011).

Stages of Material Flow ^a	Data Requirements	Data Source/Approach to Fill Data Gaps
	Share of equipment entering storage Length of storage by consumer segment	<p>Trade association data or market sales data could also be purchased in the future.</p> <ul style="list-style-type: none"> ▪ <u>Life span</u>: Use the Weibull distribution in the MFA; this incorporates the life span for new and reused products (i.e., total life span that is not broken out by first, second, third, etc. life). Conduct an internet search for average lifetimes of products within the scope, compare to those used in EPA 2011 and other literature to funnel into the Weibull distribution data. ▪ <u>Storage</u>: Use the Weibull distribution; this factors into the total life span, thus storage is theoretically applied. Alternatively, separate storage factors could be applied and obtained from an internet search for average storage times of products within the scope of work.
Collection of Covered Electronic Devices in State Legislation (B)	Total weight collected (by product category) in 2014 Rural and urban total weights	<ul style="list-style-type: none"> ▪ <u>Product weights</u>: Use average product weights for product categories in EPA (2011) and those presented in Section 3.5.2 of this report. ▪ <u>Weight collected</u>: For states with existing e-waste legislation, annual reported data for quantities collected were reviewed to ensure that modeled estimates included these quantities.
Collection from Entities Not Covered by State Legislation (C)	Total weight collected (by product type) in 2014	<ul style="list-style-type: none"> ▪ <u>Weight collected</u>: Subtract the quantity collected under state programs from the amount of e-waste generated to get the weights collected from entities not covered under those programs.
Reused Electronics (D)	Life expectancy of refurbished equipment	<ul style="list-style-type: none"> ▪ <u>Weight reused</u>: Use the Weibull distribution in the MFA; this incorporates the life span for new and reused products. Industry surveys would also inform the quantity of electronics that are refurbished and sold for reuse. ▪ <u>Life span for reuse</u>: Use the Weibull function, which accounts for the total life span of a product. In other words, there would not be a separate reuse factor.
Recycled Electronics (E)	Total weight sent to domestic recycling facilities in 2014 Total weight sent to domestic and international downstream vendors, or transferred to international recycling facilities	<ul style="list-style-type: none"> ▪ <u>Weight recycled</u>: Estimating the proportion of e-waste that is recycled will require additional effort through Industry data collection that will inform the composition of the used electronics stream.
Disposed Electronics (F)	Fraction of materials disposed of in a landfill or waste-to-energy facility in 2014 Considers all consumers, collectors, and domestic recycling facilities	<ul style="list-style-type: none"> ▪ <u>Weight disposed of</u>: Estimating the proportion of e-waste that is disposed of in landfills will require additional effort through Industry data collection that will inform the composition of the used electronics stream.

^a Letters in parenthesis refer to portions of the process illustrated in Figure 3-1.

3.5.1 Product Sales

The model relies on national sales data by year and product type for 1980 through 2007 available from EPA (2011). The authors of that report used International Data Corporation (IDC) shipment data for computers, hard copy devices, keyboards, mice, CRT, and flat-panel computer monitors.

The U.S. product sales data used in EPA (2011) across the time series of 1980 through 2007 are used for the electronics considered within the scope of this report. Sales data used in the EPA (2011) report for 2008 through 2010 was extrapolated based on prior year sales data. To supplement this information, sales data were compiled from 2011 through 2014 for the electronics included within the scope of this report (Mearian [2014] for flat-panel TVs; Entner [2015] for mobile phones; and Roy [2015] for tablet computers. Table 3-3 presents the data developed for 2008 through 2014.

Table 3-3. U.S. Electronic Sales Data from 2008 Through 2014 (Million Units)

Product	2008	2009	2010	2011	2012	2013	2014
Desktops	30.5	26.3	23.5	21.9	20.3	18.7	17.9
Portables	34.1	46.4	40.4	35.5	30.6	25.7	24.5
Hard copy peripherals	33.1	29.5	29.4	26.2	23	19.8	16.6
Mice	30.5	26.3	23.5	21.9	20.3	18.7	17.9
Keyboards	38.4	33.1	29.6	27.6	25.6	23.6	22.5
PC CRTs	0.1	0	0	0	0	0	0
PC flat panel	32.7	27.2	27.5	25.6	23.7	21.9	20.9
Color CRTs < 19 inches	0.4	0.1	0	0	0	0	0
Color CRTs > 19 inches	0.9	0.3	0.1	0	0	0	0
Flat-panel TVs	29.1	32.1	33.7	38	37.5	34	34
Color projection TVs	1.1	0.6	0.3	0.1	0	0	0
Monochrome TVs	0	0	0	0	0	0	0
Cell phones	198.3	216.1	235.6	213.1	190.5	168	143
Tablet computers	0	5.4	10.8	26.6	37.9	46.6	53.2

Note: Data for years 2008 through 2010 are from EPA (2011). References for years 2011 to 2014 include Mearian (2014) for flat-panel TVs; Entner (2015) for mobile phones; and Roy (2015) for tablet computers.

Note that CRT computer monitors and TVs, projection TVs, and monochrome TVs are no longer sold in the United States; desktop and portable computer sales have declined since 2010; and tablet computers have emerged as a new category of computer since the EPA (2011) report, with more than 53 million units (or approximately 30,000 metric tons [mt] assuming an average weight of 0.6 kilograms [kg] per tablet) sold in 2014.

3.5.2 Product Weights

The weight or mass of each product type is another critical parameter in the model that provides some estimate of the amount of electronics entering EOL management each year. Recent published estimates of electronic products weights given in Duan et al. (2013) and Wang et al. (2013) were generally comparable with those found in EPA (2011) except for

flat-panel TVs and monitors. Table 3-4 presents the updated average weights for each electronic product category from 2008 through 2014.

Table 3-4. Average Weight by Product Category in 2014 (kg)

Electronic Product	Average Product Weight
Desktops	10.0
Portables	2.9
PC CRTs	14.1
PC flat panels	11.2
Keyboards	1.3
Mice	0.1
Hard copy peripherals	7.9
Color CRTs < 19 inches	18.6
Color CRTs > 19 inches	33.1
Flat-panel TVs	9.8
Color projections	63.5
Monochromes	18.6
Cell phones	0.1

With respect to flat-panel TVs, the EPA (2011) analysis used *Consumer Reports Buying Guides* from 2008 and 2009 and online manufacturer specification sheets. EPA (2008) provided an average weight of 13.2 kilograms (kg) for flat-panel TVs beginning in 1999 and ending in 2007 (the last year with data in that report). EPA (2011) also presented a weight 13.2 kg for 1998 but found an average weight for 2008 of 34.3 kg, an average weight for 2009 of 36.6 kg, and an average weight for 2005 of 27.8 kg. A linear regression for years between 1998 and 2005 was developed based on the new data for 2005 through 2009. The EPA model was updated with this new trend line; the 13.2 kg value for the year 1998 noted in the 2008 EPA report was used for all previous years up through the 1998 model year. After 1998, the trend of increasing TV weight began. See Appendix B of this report for additional details about the data sources used to develop these trends in product weights.

Based on a review of light-emitting diode (LED) and plasma units manufactured since 2010 to evaluate the trend in U.S. flat panel-TV weights since 2010, the average weight of flat-panel TVs increased from 15.7 kg in 2004 to 16.7 kg in 2005, and then decreasing steadily to 10.1 kg in 2010, and thereafter remaining at approximately 9.5 kg to 9.9 kg. For this reason, the weights for flat-panel TVs were revised across the time series of product sales and can be broken down into two groups. From 1998 to 2004, the average market share-

adjusted flat-panel weight is 15.7 kg. From 2004 to 2015, we apply unique values for the average market share-adjusted flat-panel weights falling from 16.7 kg in 2005 to 9.8 kg in 2014. Appendix B provides more detail on the calculation of average market share adjusted flat-panel TV weights.

3.5.3 Product Lifetimes

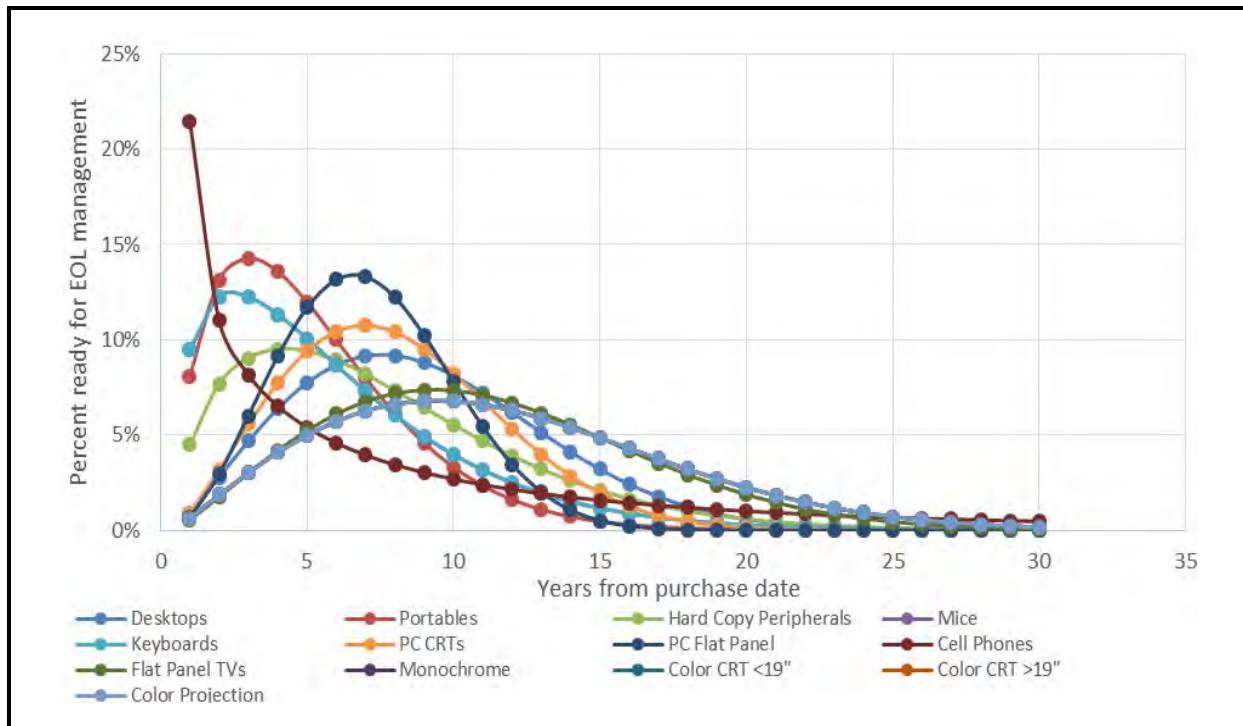
Table 3-5 presents shape and scale parameters found in the literature for various electronics. Additional information about Weibull distribution and its advantages are discussed in Appendix B of this report.

Table 3-5. Weibull Distribution Characterization Parameters in Year 2005 for Various Electronic Products

Electronic Product	Shape (α)	Scale (β)
Desktop computer (residential)	2.1	9.6
Portable computer (residential)	1.5	5.2
Cell phone	0.7	7.6
Flat-panel TV	2.1	12.6

Source: Wang et al., 2013.

Using the shape and scale parameters, continuous distributions were developed for the eWFM. Figure 3-2 presents these distributions by product type. Each point on the curve represents the percentage of equipment discarded each year after its original purchase date. Cell phones and portable computers have very short lifetimes (i.e., smaller scale values), whereas desktop computers and flat-panel TVs tend to have longer lifetimes (i.e., larger scale values). Flat-panel TVs also have a large spread in their lifetimes (i.e., a large shape parameter) compared to the other electronic products included in Table 3-5.

Figure 3-2. Percentage of Products Ready for End-of-life Management After Each Year of Sale

3.5.4 Market Segmentation

Allocating the distribution of electronic products across consumer segments and regions allows the model to track product amounts more accurately. In this way the model may serve as an analytical tool that enables policy makers to conduct uncertainty analyses and improve model assumptions with better information as it becomes available.

As mentioned earlier in this section, the proof-of-concept model currently includes four major consumer markets: residential, educational, commercial, and institutional. The default distributions by product type are based on data included in EPA (2011).

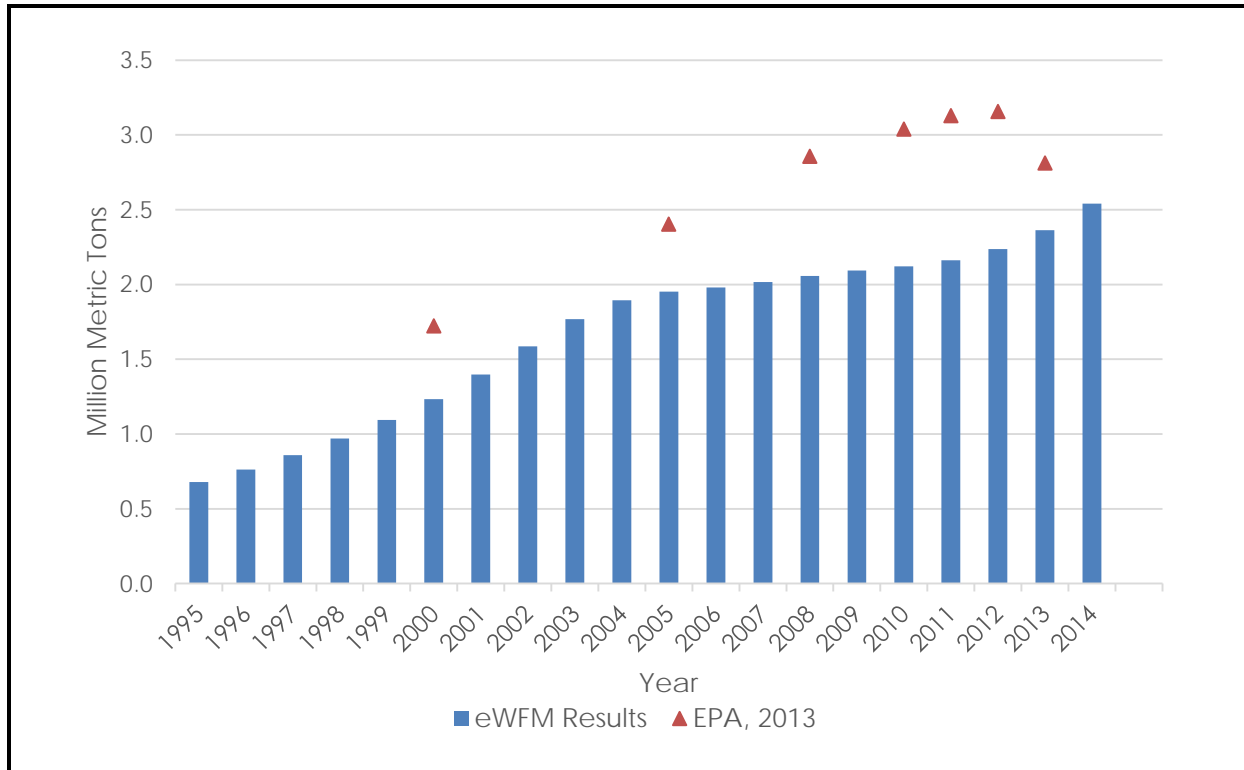
State distributions of sales data within the model are currently based on the state share of national GDP. States' share of GDP is a proxy for estimating the distribution of national product sales data. The population is an alternative metric that can be used to estimate the distribution of national sales across states. Barring more detailed sales data at the state level, the decision to use GDP, population, or some other metric should be a topic of further research to determine which explanatory variable best predicts consumer electronic purchases.

3.6 Model Results

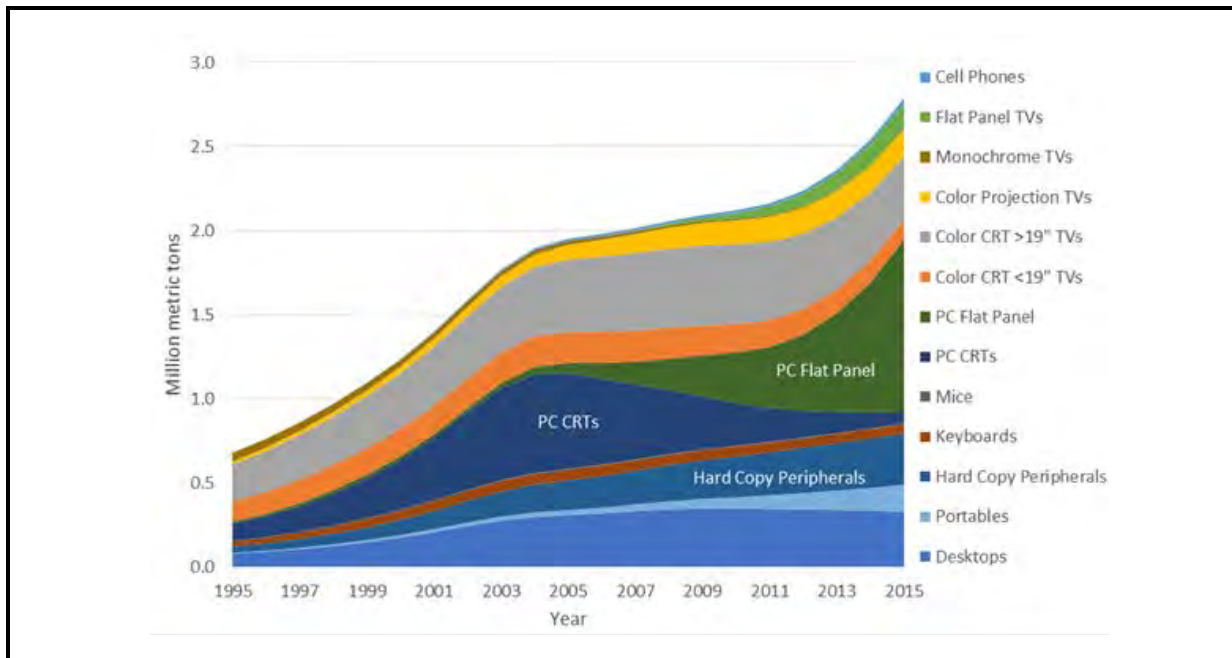
This section presents the results from the current proof-of-concept model using the data discussed earlier in this chapter. The total e-waste tonnage presented represents the quantity of products entering EOL management each year with no additional reuse. The number of units and the corresponding metric tons (mt) represent a heterogeneous mix of products entering EOL management each year with some being older and some shares being relatively newer. Hence the ratio of tonnage to number of units reflects a weighted average of mass per unit across the age distribution of products being retired in a given year.

3.6.1 National-Level Results

Figures 3-3 and 3-4 present the total amount of e-waste estimated by the model to be ready for EOL management from 1995 to 2014. The total e-waste amount has risen from 680,000 mt to more than 2.5 million mt over the past 20 years. Comparing 2013 estimates from EPA (2015) to the modeling results, the current model estimates are 350,000 mt less. The updates made to product weights and technical lifetimes discussed in this report drive the discrepancy between the two estimates.

Figure 3-3. eMFW Modeled Estimate of E-Waste Available for EOL Management: 1995 to 2014

As Figure 3-4 shows regarding eMFW model results, the most notable contributions to new growth over the past 10 years are flat-panel PC monitors and flat-panel TVs. Portable PCs, which includes laptops, are another growth category; however, the emphasis on size and portability for this product category has resulted in the relatively small contribution to total weight. Hard copy peripherals are also growing over time, possibly reflecting the decrease in price for common equipment used with PCs such as printers and scanners. CRT TVs remain a relatively large fraction of the total tonnage entering EOL management each year. Conversely, CRT PC monitors should be on the decline. Finally, based on results from the model (rather than state-level program reported data), cell phones are a very small fraction of the total tonnage because of their relatively small weight and the well-established programs aimed at their collection and reuse.

Figure 3-4. Total E-Waste Disposition by Product Type 1995 to 2015

3.6.2 State-Level Results

Table 3-6 reports the model-estimated amount of e-waste ready for EOL management in 2014 for the six states included in this evaluation. The combined amount of e-waste entering EOL management in Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin represents approximately 11 percent of the nation's total amount in 2014 or 318,000 mt.

Illinois, which is the fifth largest state in terms of national population and contribution to GDP and the largest state in the cluster evaluated here, accounted for 28 percent of e-waste among the six states. Second largest was Ohio, accounting for another 21 percent of the total e-waste. Michigan contributed 18 percent of the waste. Indiana, Minnesota, and Wisconsin accounted for nearly equal shares of the remaining 33 percent of e-waste available for EOL management in 2014.

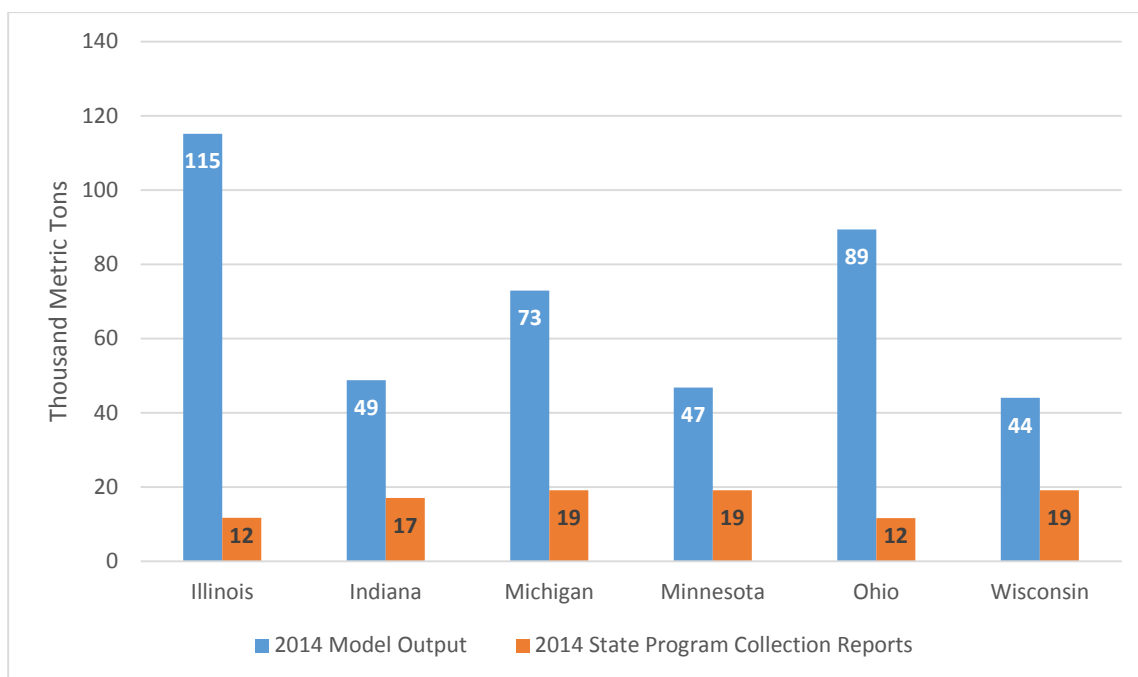
The comparison of state reported collection and model estimates is shown in Figure 3.5. Wisconsin's E-Cycle program reports that the state collected 13,600 mt of e-waste in program year 6 (July of 2014 through June 2015). The Wisconsin program's reported value is approximately 30 percent of the total e-waste estimated for the state in the proof-of-concept model. As a high-level check, this seems reasonable given that Wisconsin's E-Cycle program is limited in coverage to the residential and kindergarten through twelfth grade (K-12) education segments. Commercial and institutional segments of the consumer markets would then be estimated to account for the remaining 30,400 mt of e-waste generated in

Wisconsin. The linkage between model results and state-level program data will need to be validated during future efforts.

Table 3-6. Total Disposition Weight (in mt) by Selected State in 2014

Products	Illinois	Indiana	Michigan	Minnesota	Ohio	Wisconsin	Total
Desktops	15,029	6,360	9,405	6,122	11,585	5,746	54,246
Portables	6,006	2,561	3,568	2,479	4,576	2,313	21,503
Hard copy peripherals	13,161	5,587	8,037	5,391	10,086	5,047	47,310
Keyboards	2,477	1,055	1,547	1,011	1,920	950	8,960
Mice	126	54	79	52	98	48	458
PC CRTs	4,529	1,914	3,143	1,810	3,618	1,719	16,733
PC flat panels	34,224	14,547	20,427	14,107	26,031	13,145	122,482
Color CRTs <19-inch TVs	6,143	2,574	4,278	2,407	4,937	2,319	22,659
Color CRTs >19-inch TVs	19,115	8,043	13,189	7,569	15,309	7,240	70,464
Monochrome TVs	248	102	176	94	202	92	915
Color projection TVs	7,431	3,145	4,996	2,985	5,887	2,830	27,274
Flat-panel TVs	5,552	2,352	3,374	2,267	4,244	2,124	19,913
Cell phones	1,123	485	678	467	869	435	4,056
Total E-waste disposal	115,165	48,779	72,898	46,761	89,363	44,007	416,973

Figure 3-5. Comparison of Model Results with State-reported Data

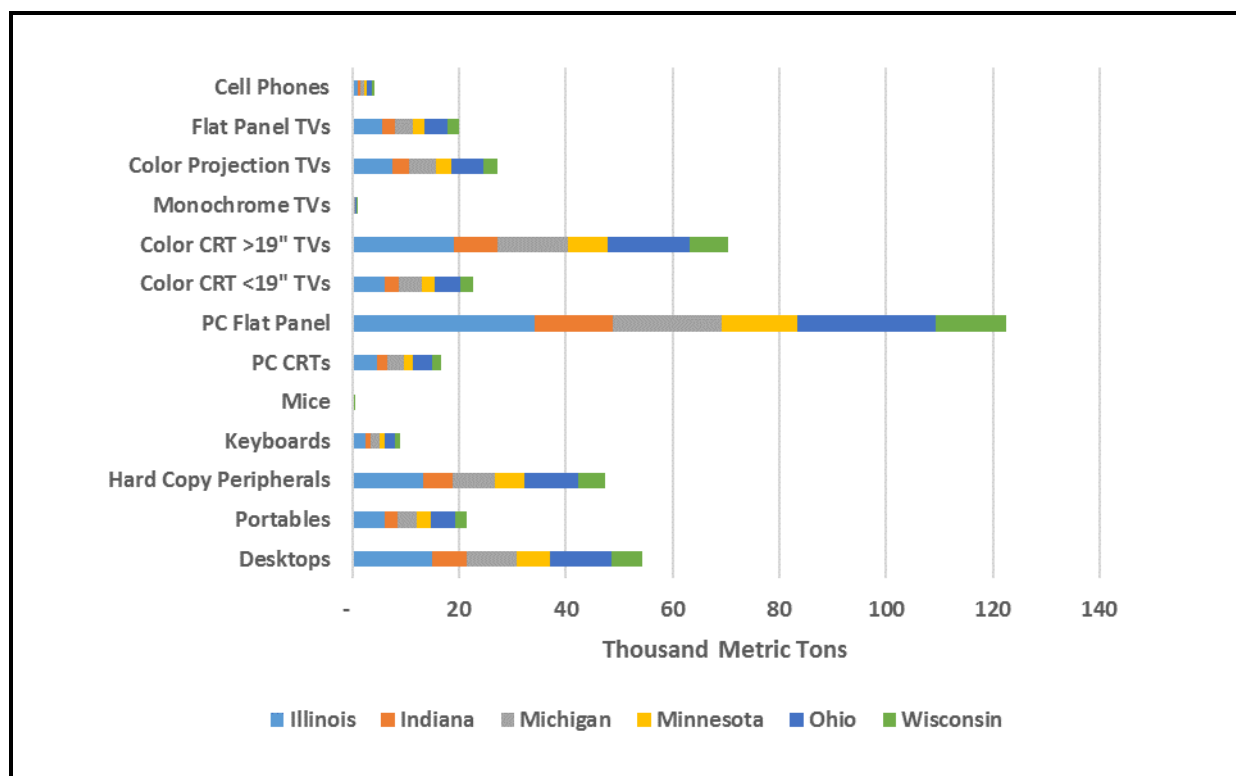


The current version of the model is not intended to be predictive of future product disposition. However, the current version of the model does provide a useful tool for estimating annual tonnage of e-waste based on a simplified number of parameters, which can assist national and state policy makers in understanding how different policy measures might change the levels of e-waste disposition. Adding sales forecast data to an enhanced version of the model could allow it to predict future product disposition and may provide additional benefits to stakeholders.

Figure 3-5 provides a graphical representation of the model-estimated e-waste amount by state and product type reported in Table 3-6. The largest volumes of e-waste are associated with flat-panel TVs and monitors. The sum of flat-panel TVs and computer monitors accounts for more than 140,000 mt (33 percent) of the total weight of e-waste for 2014. This result is surprising, given our discussions with collectors and recyclers operating in Wisconsin that reported that flat-panel TVs and monitors accounted for less than 10 percent of the annual amount of e-waste they received. There are at least three possible explanations driving the discrepancy between our modeled estimates and the observed values. One could be that the industry participants from whom we received feedback have a waste composition that is not representative of the broader industry. Secondly, the difference could also be that a significant percentage of the flat panel waste is associated with commercial entities that utilize ITAD companies that process the e-waste in other states. Finally, the product weight estimates or sales estimates used in the model may not adequately capture the total tonnage generated each year. Future research should be aimed at identifying the specific source of this discrepancy and making adjustments to the data in the model, as necessary.

CRT TVs and monitors represent the second largest contributor to 2014 e-waste, accounting for nearly 26 percent (110,000 mt) of the total e-waste. Desktop and portable PCs represent another 20 percent of the e-waste generated or just under 76,000 mt. Hard copy peripherals account for an additional 11 percent (47,000 mt). The remaining 10 percent of waste is associated with cell phones, keyboards, mice, and other types of TVs.

Figure 3-6. 2014 E-Waste Model Results by Product Type and State



4. DISCUSSION AND RECOMMENDED NEXT STEPS

Increases in household income coupled with rapid technology development and falling prices have resulted in increased consumption of consumer electronics in the United States over the past two decades. The rapid growth in the consumer electronics markets and diversification in products manufactured has contributed to an equally rapid increase in the stock of obsolete equipment and devices ready for EOL management. Embodied in the stock of obsolete devices are toxic substances that can harm human health and the environment if collection and processing is not managed correctly. Many of these devices also contain recyclable components and valuable commodities such as plastics, glass, precious metals and technology metals, and rare earth minerals that can be used to produce new products. For these reasons, the need for proper EOL management of these devices that includes opportunities for beneficial use of materials has become increasingly important to individual consumers, communities, policy makers, and manufacturers.

In support of developing sustainable EOL management of electronics in the United States, the EPA is working to improve understanding of the quantity and flow of electronic devices from initial purchase to final disposition. This report is an initial inquiry that supports EPA's broader efforts by reviewing a cluster sample of existing state regulatory and voluntary programs and identifying the key lessons learned and best practices that have emerged since their inception. Additionally, the eWFM and the MFA analysis presented in this report provides estimates of the quantity of e-waste generated annually at the national level as well as for the states analyzed here. Future research and modeling work are needed to develop the model further. Specifically, improvements can be made to estimate the movement of waste through the EOL management phase, identifying the different flow streams of e-waste from the point of collection to its final disposition (e.g., recycled for use in new electronic products, landfilled).

Previous national estimates of e-waste tonnage averaged nearly 2.8 million mt in 2013 (converted from the 3.1 million short tons as presented in Figure 1-1 (EPA, 2015)). The eWFM, presented in Section 4, of this report, estimates 2.5 million mt for the same year. Comparing the model estimates with previously published estimates, there is approximately 16 percent difference which shows that the initial model provides reasonably similar levels of e-waste tonnage compared to previous estimates. The differences are likely explained by the enhancements we have made to the EPA approach to modeling e-waste. Utilizing a Weibull distribution for the expected technical lifetime of electronic devices has smoothed the timing and rate at which a specific vintage of products enters the EOL management

phase of their life cycle. Also, updating and refining the average product weights improves our characterization trends in decreasing size of products focused on portability such as laptop PCs and smart phones. Finally, this analytical framework increases the resolution of e-waste estimates from the national level to a state level. While adding this dimension to the analytical framework does not improve or necessarily change the national estimates, it does provide greater insight into regional e-waste flows. Estimating the amount of e-waste processing occurring in each state provides a better understanding of the EOL management phase and the point of final disposition. This increased resolution could assist state and local policy makers in the design, evaluation, and improvement to e-waste management policies and programs.

When comparing the 2014 model estimation for the selected states with state-level annual reporting programs, we see a significant deviation in the state-reported data from the modeled results. There is also a large volume of used electronics coming from large organizations and corporations that are not reported in the state collection programs. Table 4-1 shows the total e-waste estimates for 2014 from the model and the program reported amount for the selected states. As mentioned earlier, state programs vary based on their product consumer segment coverage and as such, the state results should be considered individually based on the specifics of each state's program. Wisconsin, Minnesota, Indiana, and Michigan are capturing between 35 percent and 43 percent of the estimated annual e-waste amount. Comparatively, Illinois and Ohio appear to be capturing less than 15 percent of their total modeled e-waste flow estimates. The results for Illinois are particularly surprising given that it is the fifth largest state in the country based both on population and contribution to total GDP as well as a state with e-waste legislation. A possible explanation for these differences could be that products purchased and originally used in one state could be recycled in a different state. However, data currently available have insufficient detail to confirm how much e-waste crosses state borders at this phase of EOL management. Appendix A of this report includes a series of maps that identify the locations of collection and recycling facilities that are registered with state programs. As can be seen, some of these facilities are located outside of the state where the product is purchased.

Several potential factors may be driving the difference between state-reported values and the modeled estimates. For example, in states with no formal E-Cycle programs, such as Ohio, the amount of e-waste reported is limited to the amount that arrives at electronics recycling sites, collection events/sites, or landfill disposal sites. A much larger proportion may be collected through voluntary collection and recycling programs that have no reporting requirements. Additionally, there are numerous data gaps and limitations in the

analytical framework that make it difficult to compare the modeled estimates to state-reported data.

This section of the report provides some discussion of the data gaps and limitations of the analytical framework and proof-of-concept model presented in Section 3. We also discuss the potential institutional and market changes that may impact the analytical framework and estimates of e-waste in the future and conclude the report with a discussion of recommended next steps.

Table 4-1. Comparison of Model Results with State-reported Data

State	Metric Tons (% of model estimate)		Products Covered Under State Program
	2014 Model Output	2014 State Program Collection ^a	
Illinois	115,165	11,742 (10%)	Desktop computers, laptops, TVs, monitors, printers, fax machines, scanners, computer peripherals, MP3 players, video game consoles, VCRs, DVD players
Indiana	48,779	17,092 (35%)	Desktop computers, laptops, TVs, monitors
Michigan	72,898	19,108 ^b (26%)	Desktop computers, laptops, TVs, monitors, printers
Minnesota	46,761	19,135 (41%)	Laptops, TVs, monitors, tablets, e-readers, digital picture frames
Ohio	89,363	11,620 ^c (13%)	No state program
Wisconsin	44,007	19,108 (43%)	Desktop computers, laptops, TVs, monitors, printers, fax machines, keyboards, VCRs, DVD players

^a State programs only include residential and primary and/or secondary schools in these states. Other consumer segments such as governmental, commercial, and institutional entities are not covered by state programs, but are included in the modeling. Data were obtained from annual program reports and/or the state program coordinator (IDEM 2014; IEPA 2015a; IEPA 2014; IEPA 2013; MI DEQ 2015; MPCA 2010; MPCA 2011; WI DNR 2014). Data for OH were provided by the state coordinator. Data for MN were extrapolated for 2012 through 2014 because annual program data have not been published online as of the date of this report.

^b Michigan data are representative of CEDs and EEDs recycled by registered recyclers under Michigan's state program. Data on collection is not available because the state program does not cover collection sites (i.e., they are not required to track and report electronics collected).

^c Ohio data are derived from Annual District Reports (ADR) for Recycling and Disposal from each Solid Waste Management District in the state. This value is from the 2013 ADR because the 2014 report had not been published at the time of data retrieval.

4.1 Data Gaps and Limitations

The results of the analysis presented in this report cover the major consumer electronic products, key consumer segments, and potential pathways to final disposition. However,

there are numerous data gaps and limitations to the current analysis framework that need to be considered.

4.1.1 Limited Use of Regional Data

The analytical framework used in this study is flexible enough to incorporate regional differences in all of the characteristics and model parameters. However, a lack of comprehensive, state-specific data has led to a reliance on expert judgment or national averages being applied uniformly to all states. Greater use of state- or region-specific data regarding the collection and recycling tonnages, as well as the shares of e-waste processed in state and the amount of waste transported out of state for processing, are recommended for follow-up research. It is anticipated that follow-up research will include obtaining expert judgment from industry, public, and private-sector experts. Incorporating more regional data could enhance the characterization of the waste flows across state and national boundaries by estimating the amount of e-waste at each stage in the EOL management phase and its physical movement across state and national boundaries.

4.1.2 Lack of Product Sale Projections

The current analysis only includes historical sales. As a result, the model is incapable of estimating future e-waste amounts. Using projected sales data or developing sales projections would improve the value the eWFM offers to policy makers and resource planning decision makers. These types of sales data are available for purchase from market research organizations. While this would be relatively expensive to obtain, incorporating projections of sales over some time horizon would allow better estimates of long-term impacts of current markets and consumer preferences. Future effort to add this type of functionality should consider how this additional feature impacts uncertainty for projected estimates of e-waste.

4.1.3 Characterization of Regional Flows of E-Waste

Currently the model does not track the movements of e-waste across state and national boundaries. Our review of state programs revealed that the state where a device is collected for recycling does not necessarily indicate where the device will be recycled or processed (see maps in Appendix A). Depending on the processor receiving the e-waste, the collected devices could cross state lines for processing or could be preprocessed and disassembled components sold to a tertiary processor in another location. Future research should characterize the various type of processing facilities and expected destinations of the process materials. For example, they could be transported for use in production at OEM

facilities, or exported to an international destination for final disposition. It is very important to note that because of the dynamic nature of the e-waste recycling and commodities markets, the flow of e-waste may change frequently and therefore efforts to track flows must be flexible and adaptable to the ever-changing market.

4.1.4 Exclusion of Recycling Market Economics

The analysis presented here does not account for changes in recycled-product market prices. These changes in market prices are likely to have a significant impact on the processors' operational decisions. This could affect the flow of e-waste to the various final disposition channels (e.g., landfills, new products) or the timing of when the stock of recycled material actually reaches the point of final disposition. For example, when the prices for recycled products are low, a processor may choose to store material for an extended time in the hopes that prices rebound in the future. Although, notably, certain hazardous materials such as the leaded glass contained within CRT TVs is subject to RCRA speculative accumulation requirements and cannot be stockpiled in this manner. Future efforts therefore should consider alternative operational pathways based on various market conditions.

4.2 Potential Institutional and Market Changes

While there remain numerous data gaps and limitations in the current analysis framework, these modeling efforts provide valuable information on trends. The state policies and voluntary participation in programs have been changing and continue to evolve.

To date, 25 states have passed extended producer responsibility, consumer fee, or producer education laws that mandate e-waste recycling programs. Twenty-three states, including those highlighted in this report, have extended producer responsibility laws, which obligate manufacturers to facilitate and finance recycling of their EOL products. California, through its Electronic Waste Recycling Act of 2003, instituted an advanced recycling fee. Utah only requires manufacturers to establish and implement public education programs to inform consumers of eligible collection and recycling programs.

The variety of program elements and requirements allow for natural test cases to draw on the lessons learned in establishing and running an e-waste recycling program. Analyzing the successes and challenges of these programs helps identify best practices and lessons learned that other states can leverage to strengthen their recycling programs and increase their collection tonnage. For example, there is a wide disparity among per capita collection amounts across the states with programs, although this is partially explained by the

differing scope of products. Washington and Oregon reported collecting more than 5 pounds per capita of CEDs in 2010, whereas some states, including Texas and Virginia, collected less than 1 pound per capita of CEDs. States are also observing large quantities of older, heavier electronics that may not be recycled in the same program year in which they were received because the manufacturers are meeting or exceeding their specific program year goals (IDEM, 2014) and may, in turn, choose not to recycle beyond their program goals. There may be shifts in how program goals are devised in the near-term to alleviate this issue or new measures may be instituted for manufacturers to recycle these “legacy wastes.” Indiana (IDEM, 2014) and Wisconsin (WI E-Cycle Stakeholder Meetings, 2014 and 2015a) have noted cherry picking of waste, where the most valuable components in collected materials are picked out of the used electronics while the other materials are discarded. Illinois is considering incorporating recommended minimum coverage areas based on population density (IEPA, 2016); Washington, Oregon, and New York have similar population density clauses that resulted in increased collection in rural areas. None of the selected states evaluated in this report have these type of siting clauses. Collection sites that do not operate year-round or do not accept all CEDs or damaged CEDs may be investigated by a select state. In Illinois, for example, these were noted as key issues to discuss going forward (IEPA, 2016).

4.3 Recommended Next Steps

The current proof-of-concept version of the e-waste tracking tool has leveraged existing EPA work to develop national, regional, and state-level e-waste estimates. However, there are several recommended next steps that we see as critical to continued refinement of the model. These next steps can be categorized into three areas that include improved functionality, calibration using other data sets, and addition of features for evaluating transport of flows across state and national boundaries. Completing these steps will enhance the characterization of e-waste flows in terms of location, final disposition to landfills and incinerators, and utilization in new products.

Improvements in functionality that will improve usability of the model for a broader set of end users includes adding an interface to the model that allows users to quickly compare different states or groups of states. This interface will link the state-level estimates to a dynamic map that would visually represent the modeling results based on the parameters specified by the user regarding year, product, and consumer segment.

Another critical next step is to calibrate the model using available estimates of e-waste collected by state programs combined with information from major recyclers on the balance

of e-waste not captured under the legislative programs. Most of the state programs reviewed for this analysis focus on residential and institutional consumer segments. The balance of e-waste is generated by the commercial sector. There are however limited sources of published estimates from this sector. We recommend attending key stakeholder meetings in selected states or holding industry focus groups at national e-recycler conferences, such as the E-Scrap Conference.

More work is also needed to estimate the final disposition for e-waste once it enters the EOL management process to model the collection and recycling processes and estimate e-waste volumes based on their final disposition (e.g., sale as raw materials, refurbishment, disposal in a landfill). Previous work by EPA estimates these shares by final disposition result. We would seek to update or confirm that these estimates reflect current conditions and provide additional information on the physical movements of e-waste across state and national boundaries.

Estimating quantities and market value of e-waste components (e.g., plastic, circuit boards, copper, other technology metals) is another potential output of the model that could be developed and could support decision making with respect to beneficial use of materials. Adding this component would require developing a database (or a method for linking to current databases) on current market prices for the components of e-waste products. It is important to note that adding this type of data would add significant uncertainty due to the variation in components of manufactured electronic products and the dynamic nature of the market.

Finally, additional work could be undertaken to better characterize the economics of operations at EOL management processing facilities. This information would be useful for understanding the market dynamics and operators' responses to changes in international prices for the various fractions of e-waste, such as glass, plastic, and metals. This would include characterizing the types of recycling facilities common throughout the industry and include the types of equipment used in processing operations, labor requirements, cost of operations, and potential revenue streams, based on current market prices for recycled and refurbished electronic products. Improving our understanding of the economic drivers for the industry could also support a more formal economic impact assessment in the future.

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Appendix A: Additional Detail on Selected State and National Programs

This appendix provides additional details on the selected state programs as well as national efforts that are under way related to the end-of-life (EOL) management of used electronics.

A.1 Products Covered by Legislation in the Selected States

The selected states with e-waste laws and programs offer free collection and recycling of covered electronic devices (CEDs) for households, K–12 public schools, and small businesses. Table A-1 presents the CEDs in the selected states. Two states (i.e., Michigan and Indiana) also offer free collection and recycling for businesses, although Indiana has a caveat that the covered business must be deemed a “small business,” which they define as employing fewer than 100 people. Michigan allows both households and businesses to recycle their used electronics at no cost with a limit of seven items in a single day.

Table A-1. Product Coverage in the Selected States with Used Electronics (E-waste) Laws

State	Televisions		Monitors		Computers		Mobile Phones	Other Devices
	CRT	Flat Panel	CRT	Flat Panel	Portable	Desktop		
IL	✓	✓	✓	✓	✓	✓	✓ ^a	CEDs: Printers, fax machines, scanners, mice, keyboards, MP3 players, video game consoles, VCRs, DVD players EEDs: Computer cables, PDAs, zip drives
IN	✓	✓	✓	✓	✓	✓ ^a		CEDs: Printers, keyboards, fax machines, VCRs, DVD players
MI	✓	✓	✓	✓	✓	✓		CEDs: Printers
MN	✓	✓	✓	✓	✓	✓ ^a		CEDs: Tablets, e-readers, digital picture frames (whose displays are 9"+ diagonally) EEDs: Keyboards, mice, fax machines, DVD players, VCRs, any device sold exclusively for external use with a computer that provides input or output from a computer
WI	✓	✓	✓	✓	✓	✓		EEDs: Printers, keyboards, fax machines, DVD players, VCRs

Note: CED = covered electronic device; EED = eligible electronic device.

^a The product is not a CED according to state law, but it is considered to be an EED.

Illinois, Indiana, Michigan, and Minnesota have large scopes of CEDs within their collection and recycling programs that include other electronic devices common in U.S. households that are not specifically covered by the state program, such as VCRs, DVD players, printers, and other computer peripherals. Minnesota's e-waste program also covers "any other device sold exclusively for external use with a computer that provides input or output in or from a computer," making its program one of the most comprehensive of those evaluated here.

The program in Illinois is the only one in the selected states that includes mobile phones from households as a CED. The lack of coverage for mobile phones across the selected state laws may be surprising as mobile phones are ranked third in the CTA's Most Owned Tech by U.S. Households (CTA, 2015). However, there are numerous mobile phone EOL management methods available to the consumer, such as selling them to a third party vendor (e.g., Gazelle, uSell), and donating or selling them back to a retailer or manufacturer (e.g., Verizon).

A.2 Program Registration and Funding Mechanisms

A.2.1 Program Registration

To monitor the activities of manufacturers, collectors, and recyclers and to track, validate, and enforce their goals under the directive of each state's recycling program, most entities participating in the state programs are required to register each year with the ruling body. The states included in this evaluation prohibit manufacturers from selling their products, either directly or through a retailer, in their state if the manufacturer does not register with the program. Annual registration is required as opposed to a one-time registration to more closely track trends in compliance and collection, which assists the ruling body of the program in evaluating what aspects of the program are working and which need improvement. Table A-2 indicates, by state, whether the manufacturer, collector or recycler have to register with their respective state program. Michigan has the fewest registration (and reporting) requirements, while Illinois has the most stringent requirements, including requiring refurbishers to register.

Table A-2. Entities that Must Register Under the Selected State Programs

State	Must Register?			
	Manufacturers	Collectors	Recyclers	Refurbishers
IL	✓	✓	✓	✓
IN	✓	✓	✓	X
MI	✓	X	✓	X
MN	✓	✓	✓	X
WI	✓	✓	✓	X

The specific manufacturer registration requirements by state are provided in Table A-3. All states require OEMs to register, and they must report (1) the weight of CED sales in the current or previous year, or (2) the weight of CEDs collected by the OEM in the previous year. The enforcing agency uses these data to create a recycling goal for each OEM for the next program year. OEMs generally report this information in their annual report. For example, Indiana and Michigan require OEMs to provide the total weights of the CEDs manufactured during the previous year in their annual registration. Michigan simply tasks manufacturers with reporting the total weight of CEDs they received from their takeback program in the previous year. Indiana requires manufacturers to estimate the weight of CEDs sold during the previous 12 months based on sales data, whether those data are state-specific or national sales data apportioned to the state's population.

Michigan is the only state that does not require manufacturers to disclose whether any of their CEDs sold to households within the state exceed the maximum concentration values established for certain hazardous substances under the Restriction of Hazardous Substances (RoHS) Directive⁴ adopted by the European Union. The directive restricts the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, and polybrominated diphenyl esters because high concentrations of these substances have proven to be harmful to human health. Manufacturer disclosure of devices containing these substances can help inform collectors and recyclers working with the manufacturer of any additional protocol they may need to follow in order to ensure worker safety.

⁴ For more information about the European Union's RoHS Directive, see http://ec.europa.eu/environment/waste/rohs_eee/index_en.htm.

Table A-3. Manufacturer Registration Requirements Under the Selected States' Programs

State	Requires List of Brands?	Requires Data on Weight of CEDs?	Requires Certification of Compliance With State and Federal Laws?	Additional Requirements
IL	Yes	No Manufacturer's annual report only, based on sales records or national sales data	Yes	Disclosure as to whether any video display devices sold to households exceed maximum concentration values established for substances under the RoHS Directive
IN	Yes	Yes An estimate (based on sales data) of the total weight in pounds of the manufacturer's video display devices sold during the previous 12 months	Yes	Demonstration as to how the manufacturer plans to meet their recycling goal for the upcoming program year Disclosure as to whether any video display devices sold to households exceed maximum concentration values established for substances under the RoHS Directive
MI	Yes	Yes The total weight of CEDs received by the manufacturer's takeback program in the previous year	No	Must provide details on how the OEM is to educate consumers about how and where to return CEDs with the manufacturer's label Must detail the processes and methods used to recycle or reuse CEDs received from consumers Identification of the collector(s) and recycler(s) used by the manufacturer to handle CEDs
MN	Yes	No Manufacturer's annual report only, based on sales records or national sales data	No	Disclosure as to whether any video display devices sold to households exceed maximum concentration values established for substances under the RoHS Directive
WI	Yes	No Manufacturer's annual report only, based on sales records or national sales data	Yes	Must also include a description as to how the manufacturer calculated the weight they reported. Manufacturers are not required to report these numbers until its CEDs have been sold or offered for sale to households or schools in the state for one full program year. Disclosure as to whether any video display devices sold to households exceed maximum concentration values established for substances under the RoHS Directive

Table A-4 specifies the registration requirements for collectors, and Table A-5 details the recycler requirements for the states with electronics recycling programs and legislation that were evaluated as part of this study.

Table A-4. Collector Registration Requirements Under the Selected States' Programs

State	Must Register?	Must Report		Additional Requirements
		Where CEDs/EEDs Are Received?	Total Weight of CEDs/EEDs Collected Annually?	
IL	Yes	Yes	Yes	<ul style="list-style-type: none"> A list of each recycler and refurbisher that received CEDs and EEDs from the collector, and the total weight they received Collectors cannot recycle or refurbish unless they have also registered as a recycler/refurbisher
IN	Yes	No	No	<ul style="list-style-type: none"> N/A
MI	No	N/A	N/A	<ul style="list-style-type: none"> N/A
MN	Yes	Yes	No	<ul style="list-style-type: none"> Certification of compliance with applicable state and federal legislation
WI	Yes	Yes	No	<ul style="list-style-type: none"> Certification of compliance with applicable state and federal legislation May not use prison labor to collect CEDs and EEDs

Note: N/A = not applicable.

Illinois, Minnesota, and Wisconsin require manufacturers, collectors, and recyclers to report more detailed information, including the address of each location where they manage CEDs and EEDs and identification of each location at which they accept CEDs and EEDs from a residence, the locations they send the CEDs and EEDs to (and the weight of those items), and the weight of CEDs and EEDs collected or recycled by manufacturer. This level of detail allows for a more complete data set and understanding of the material flows. Additionally, Illinois is the only state requiring refurbishers to register with the state's program although the registration and reporting requirements for refurbishers are identical to those of recyclers in the state.

Table A-5. Recycler Registration Requirements Under the Selected States' Programs

State	Must register?	Must Report		Additional Requirements
		Where CEDs/EEDs Are Received?	Total Weight of CEDs/EEDs Collected Annually?	
IL	Yes	Yes	Yes	<ul style="list-style-type: none"> ▪ Must implement applicable environmental health and safety training measures ▪ Keep an up-to-date hazardous material management plan (details in legislation) ▪ Maintain liability insurance for accidents and emergencies ▪ Completion of an EHS audit ▪ Use of a record-keeping program that tracks inbound and outbound CED and EED weights ▪ Compliance with export laws ▪ May not use prison labor to recycle CEDs and EEDs
IN	Yes	No	No	<ul style="list-style-type: none"> ▪ N/A
MI	Yes	No	No	<ul style="list-style-type: none"> ▪ Maintain a documented EHS management system ▪ May not use prison labor to recycle CEDs and EEDs
MN	Yes	Yes	No	<ul style="list-style-type: none"> ▪ Certification of compliance with applicable state and federal legislation ▪ May not use prison labor to recycle CEDs and EEDs
WI	Yes	Yes	No	<ul style="list-style-type: none"> ▪ Certification that the recycler meets all operational requirements outlined by the rule ▪ Certification of compliance with applicable state and federal legislation requirements concerning storage, transportation, processing, and exporting EEDs and materials derived from EEDs as well as all applicable environmental, health and safety protocol ▪ Maintain liability insurance for accidents and emergencies as required by the rule (at least \$1,000,000 for environmental releases, accidents, and other emergencies). ▪ May not use prison labor

A.2.2 State Program Funding Mechanisms

Annual registration fees collected from manufacturers fund the e-waste programs implemented by the selected states. This cost model is referred to as extended producer responsibility. Table A-6 provides a summary of the annual registration fees charged to manufacturers, as well as where the collected funds are deposited and what the funds can be used for.

Table A-6. Manufacturer Fees in the Selected States with Programs

State	Registration Fee	Where is the Fee Deposited?	Uses for Collected Fees
IL	\$5,000 annually \$1,250 for manufacturers selling less than 250 CEDs in the prior calendar year Recyclers and refurbishers pay \$500 annually	Electronic waste recycling fund	Costs to administer the program Grants (\$2,000 for each recycling coordinator in each county)
IN	\$5,000 for the first year \$2,500 annually each year thereafter, plus a variable recycling fee Manufacturers producing less than 100 video display devices during the previous calendar year cannot be charged a fee	Electronic waste recycling fund Funds can be transferred to and used by the Department of Environmental Management	Costs to administer the program If registration fees are in excess of administration costs, money is prorated back to manufacturers
MI	\$3,000 annually If the electronic waste recycling fund has more than \$600,000 in any year, the department shall not charge manufacturers a fee the following program year	Electronic waste recycling fund	Costs to administer the program Pay outreach and education programs designed to provide residents with information and opportunities to recycle electronics
MN	\$2,500 annually plus a variable recycling fee Manufacturers producing less than 100 video display devices during the previous calendar year are charged \$1,250 annually	Electronic waste recycling fund	Costs to administer the program Grants to counties and private entities operating in rural areas
WI	\$5,000 annually \$1,250 for manufacturers that sell at least 25 but less than 250 CEDs during the previous calendar year Fee waived for manufacturers selling less than 25 CEDs	Electronic waste recycling fund	Costs to administer the program

Illinois is the only state that was evaluated here that requires recyclers and refurbishers to pay an annual fee with the submittal of their annual registration. When Illinois' program began in 2010, recyclers were required to pay a fee of \$2,000 along with their annual registration. In 2011, the state decreased the fee to \$500 for those recyclers and refurbishers that collect less than 1,000 tons per year from registered manufacturers. From

2012 forward, the fee charged to recyclers and refurbishers increases by an inflation factor determined by the annual Implicit Price Deflator for GDP⁵ for the previous program year.

The annual registration fees are primarily used to administer the electronics recycling program within a given state. Some states allow the funds to be used for other purposes that benefit registrants and aid them in meeting their year-to-year targets. For example, in Indiana, money remaining in the fund at the end of the fiscal year may be used to make loans to assist: (1) persons in establishing new recycling businesses, (2) in the expansion of existing recycling businesses, and (3) manufacturers in retrofitting equipment necessary to reuse or recycle secondary materials. Additionally, in Illinois, Indiana, and Minnesota, remaining funds can be used to provide grants to program participants. Specifically, Illinois apportions \$2,000 from the fund annually to each county's recycling coordinator so that they may boost collection and recycling operations across the state and better inform residents in each county about the electronic recycling program. Minnesota also provides grants but focuses on rural counties and private entities that operate in those rural areas. As previously noted, operating collection sites in rural areas has many challenges, including staffing, illegal dumping/drop-offs, and difficulties in collecting enough material to justify the costs of a hauler to move the material to a processing facility.

A-3 Manufacturer Recycling Goals, Credits, and Incentives

Implementing a workable, cost-effective, and efficient collection and recycling system can take time, so states frequently have set lower manufacturer recycling goals in the first year that a recycler registers under the state program. As shown in Table A-7, Illinois, Indiana, and Minnesota all have lower goals for the first year a manufacturer registers with the program to allow the manufacturer ample time to comply. Manufacturer goals in Indiana and Minnesota increase from 60 percent of the weight of previous year sales to 80 percent of the weight of previous year sales after the first year, while the program in Illinois increases over a longer period (the first year starts at 40 percent of the weight of previous year sales and increases by up to 10 percent each year thereafter). Michigan's program is

⁵ An economic metric that accounts for inflation by converting output measured at current prices into constant-dollar gross domestic product (GDP). The GDP deflator shows how much a change in the base year's GDP relies upon changes in the price level. Changes in consumption patterns or the introduction of new goods and services are automatically reflected in the deflator. For more information, see <http://www.investopedia.com/terms/g/gdppricedeflator.asp>.

the most lenient towards OEMs, with a nonbinding target of 60 percent of the weight of CEDs sold during the previous year.

Table A-7. Selected State Program Goals and Collection Incentives

State	Manufacturer Recycling Goal		Penalties for Missing recycling Goal	Incentives for Rural Areas?	Incentives for Reuse?
	First Year	Subsequent Years			
IL	≥ 40% of the total weight of electronic devices that the manufacturer sold in that category during the previous calendar year in the state	Increases by up to 10% over previous year's goal for each program year after the first	Must pay shortfall fee for pounds not collected	Yes, 2× credit for collected devices in underserved counties	Yes, 2× credit
IN	≥ 60% of the total weight of the manufacturer's CEDs sold to households as reported in the manufacturer's registration for the program year	Increases to 80% after the first year	Must pay shortfall fee for pounds not collected	Yes, 1.5× credit for rural areas; 1.6× credit for rural areas and recycling within Indiana	No
MI	Nonbinding target of 60% of the total weight of the manufacturer's CEDs sold in the state during the previous year	No change	None	No	No
MN	≥ 60% of the total weight of the manufacturer's CEDs sold in the state during the previous year	Increases to 80% after the first year	Must pay shortfall fee for pounds not collected	Yes, 1.5× credit	No
WI	≥ 80% of the total weight of the manufacturer's CEDs sold in the state during the previous year	No change	Must pay shortfall fee for pounds not collected	Yes, 1.25× credit	No

All of the selected states with legislation, except for Michigan, offer incentives for collection and recycling on behalf of manufacturers in rural areas, providing a 1.25 to 1.5 multiplier for collected weights in areas defined as rural by state legislation. Indiana offers a baseline multiplier of 1.5 for weights collected in rural areas, and also offers a small incentive of 1.1 times for weights that are collected and recycled in Indiana, regardless of whether they were collected in an urban or rural county.

Illinois is the only one of the selected states to offer incentives for reuse of a collected device. Manufacturers in the Illinois program can double the weight of any CEDs collected and processed for reuse, and can triple any weight totals for used electronics that are donated for reuse to a low-income or majority developmentally disabled primary or secondary public education institution. Illinois offers the most incentives towards manufacturer goals, including a 2 times multiplier for weights collected free of charge in underserved counties and a 3 times multiplier for weights collected on behalf of a manufacturer by a facility that qualifies as a nonprofit and has a developmentally disabled workforce of 75 percent of the total or greater.

A.4 Collection Sites

Electronics collection sites include permanent drop-off locations and temporary events (e.g., 1-day events at a specified location) that cater primarily to households. Consumers of great quantities of devices (businesses, universities, government) generally fall outside the state legislation and tend to engage in a more formal agreement with a collector, broker or recycler, an OEM, or a business in the information technology asset disposition (ITAD) sector.

Collection facilities are generally distributed across each state, with more in cities and metropolitan areas because of the higher population density and resulting higher collection volumes. While no comprehensive source exists on the challenges of used electronic collection in rural areas, those in the state programs and especially the haulers that serve the rural areas, acknowledge that there are hurdles in both cost and time associated with the rural collection. None of the state laws evaluated here include requirements with respect to the spacing of collection sites as a function of population density. Some states outside the scope of this study (e.g., Washington, Oregon, New York) include siting requirements (e.g., one collection point in every county and one in population centers over 10,000 people) to ensure that everyone in the state, no matter how rural their place of residence, has access to a collection site.

Maps of the registered collection sites for Indiana, Illinois, Minnesota, and Wisconsin are presented in Figures A-1 through A-4. Note that only the sites registered with the states' programs are presented in these maps and they do not include every type of e-waste/used electronics drop-off site, such as Verizon and Best Buy stores. The Wisconsin Department of Natural Resources (WI DNR), unlike the other states, maintains a list of 1-day and temporary events in addition to the permanent collection sites. These maps also identify the counties for which there are no collection sites. Michigan's e-waste program only requires

recyclers to register, thus the Michigan Department of Environmental Quality (MI DEQ) does not maintain a centralized list of collection sites.

Figure A-1. E-waste Collection Sites in Indiana (as of July 2015)

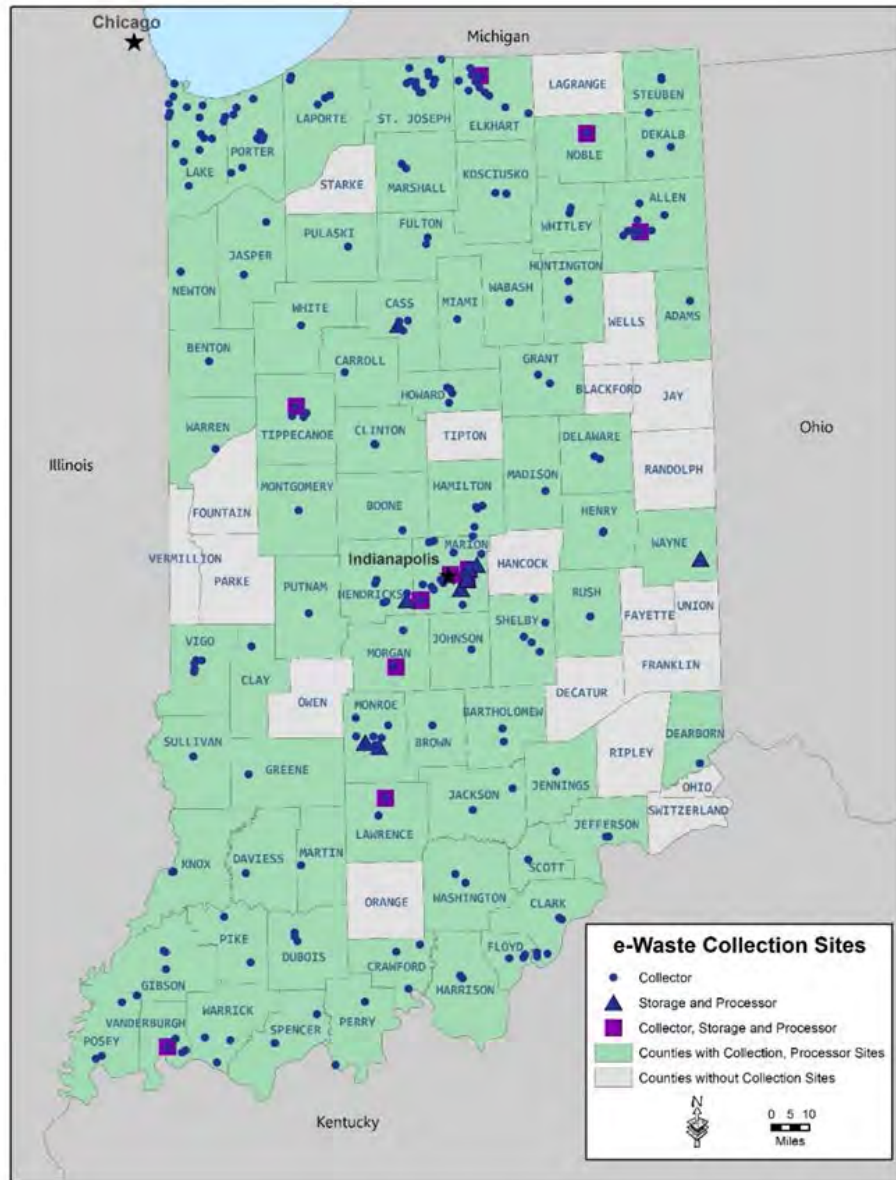


Figure A-2. E-waste Collection Sites Registered Under the Illinois Electronic Waste Management Program (as of July 2015)

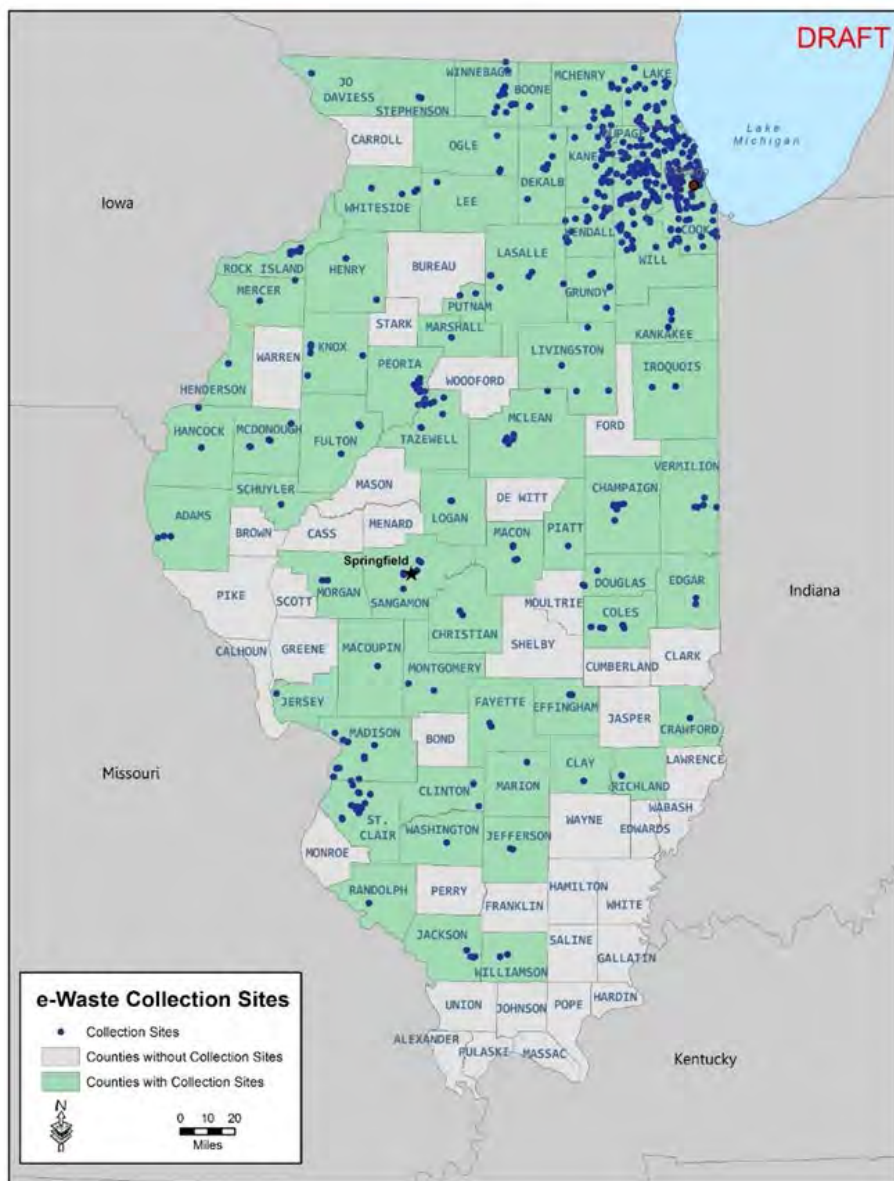


Figure A-3. E-waste Collection Sites Registered under E-Cycle Minnesota (as of July 2015)

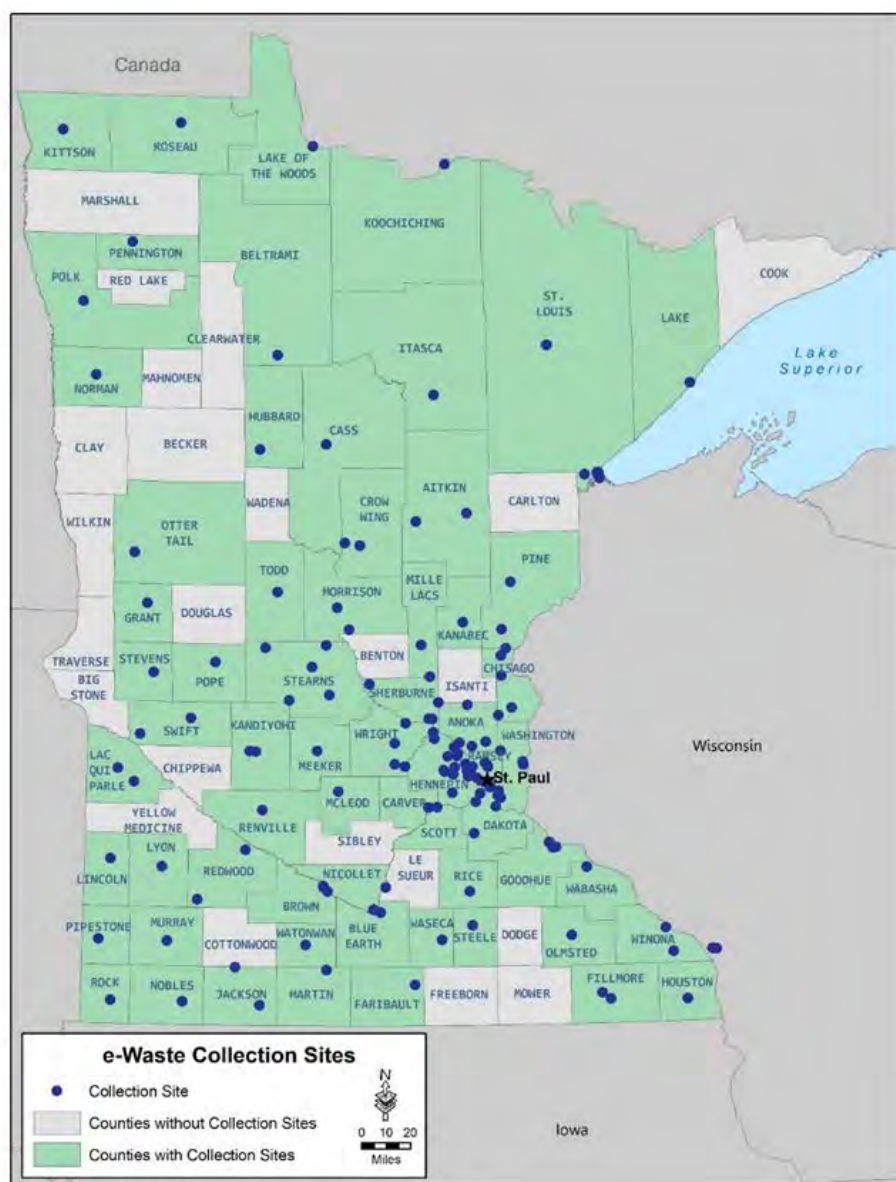
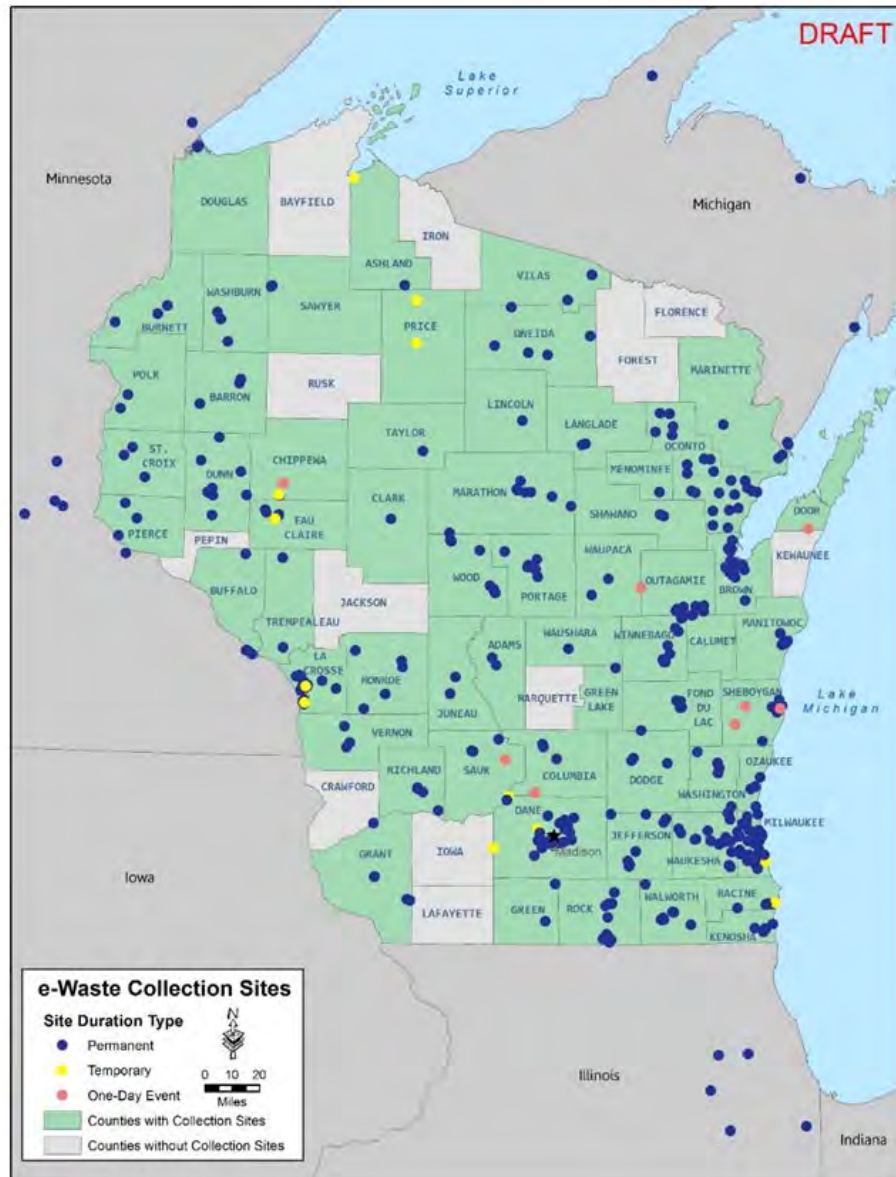


Figure A-4. E-waste Collection Sites Registered Under E-Cycle Wisconsin Located in Wisconsin (as of July 2015)



Note: The WI DNR, unlike the other states, maintains a list of 1-day and temporary events in addition to the permanent collection sites.

A-5 Processing/Recycling Facilities

Similar to the collection sites, the recycling facilities are distributed across the states. Electronics recyclers are required to register in all of the selected states with e-waste laws; however, there are most likely unregistered recyclers in operation. Like the collection site maps, counties without any e-waste processing facilities are identified in Figures A-5 through A-9. National views are presented because the materials collected are often shipped

out of state for processing. The facilities included in these maps were listed on each state's e-waste program Web site. Additionally, many recycling facilities perform multiple operations such as collecting materials and refurbishing material. Illinois is the only state included in this evaluation where e-waste refurbishers are required to register under the e-waste program; thus this information was readily available and is presented here. All other state maps present e-waste recycling facilities only.

Figure A-5. Recycling Facilities Registered Under Michigan's E-Waste Takeback Program Located in Michigan (as of July 2015)



Figure A-6. Recycling Facilities Registered Under Michigan's E-Waste Takeback Program Located Outside of Michigan (as of July 2015)

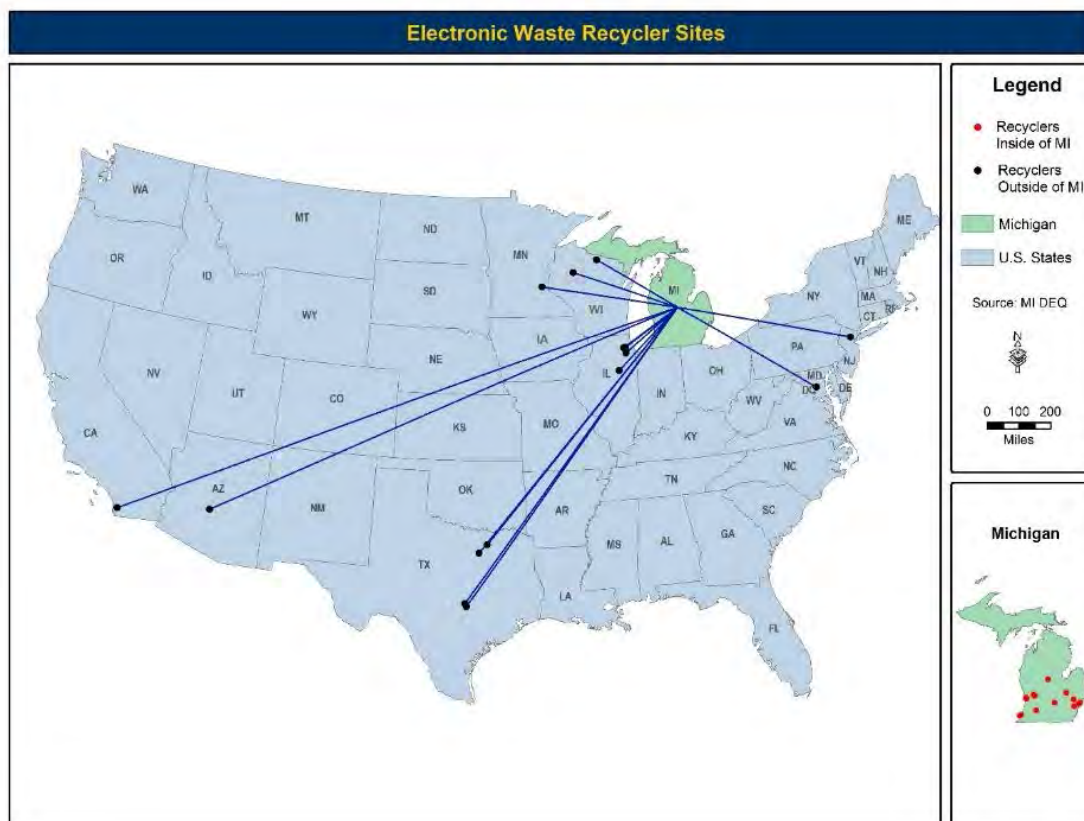


Figure A-7. Recyclers Registered Under E-Cycle Minnesota Located in Minnesota (as of July 2015)

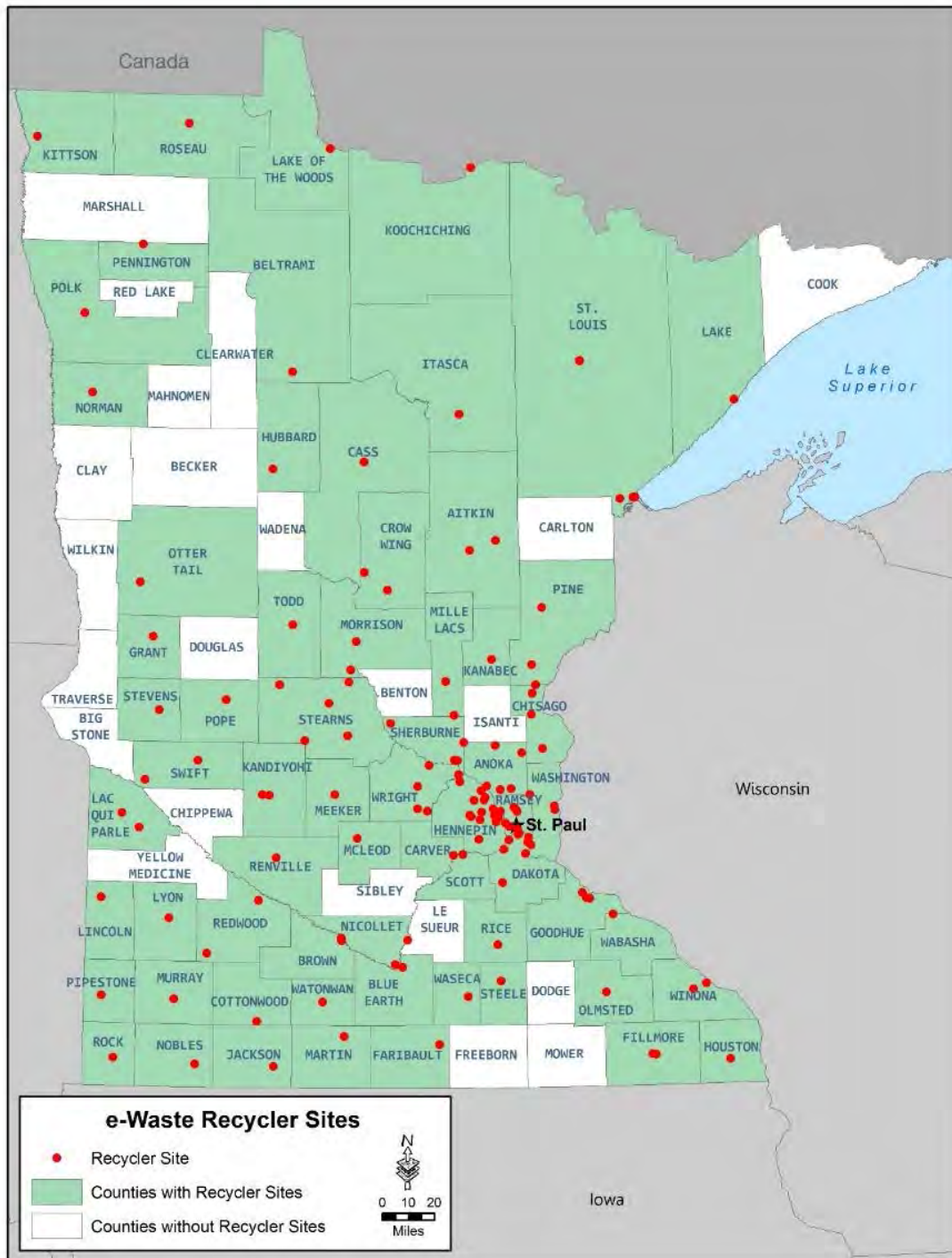


Figure A-8. Recycling Facilities Registered Under E-Cycle Wisconsin Located Inside of Wisconsin (as of July)

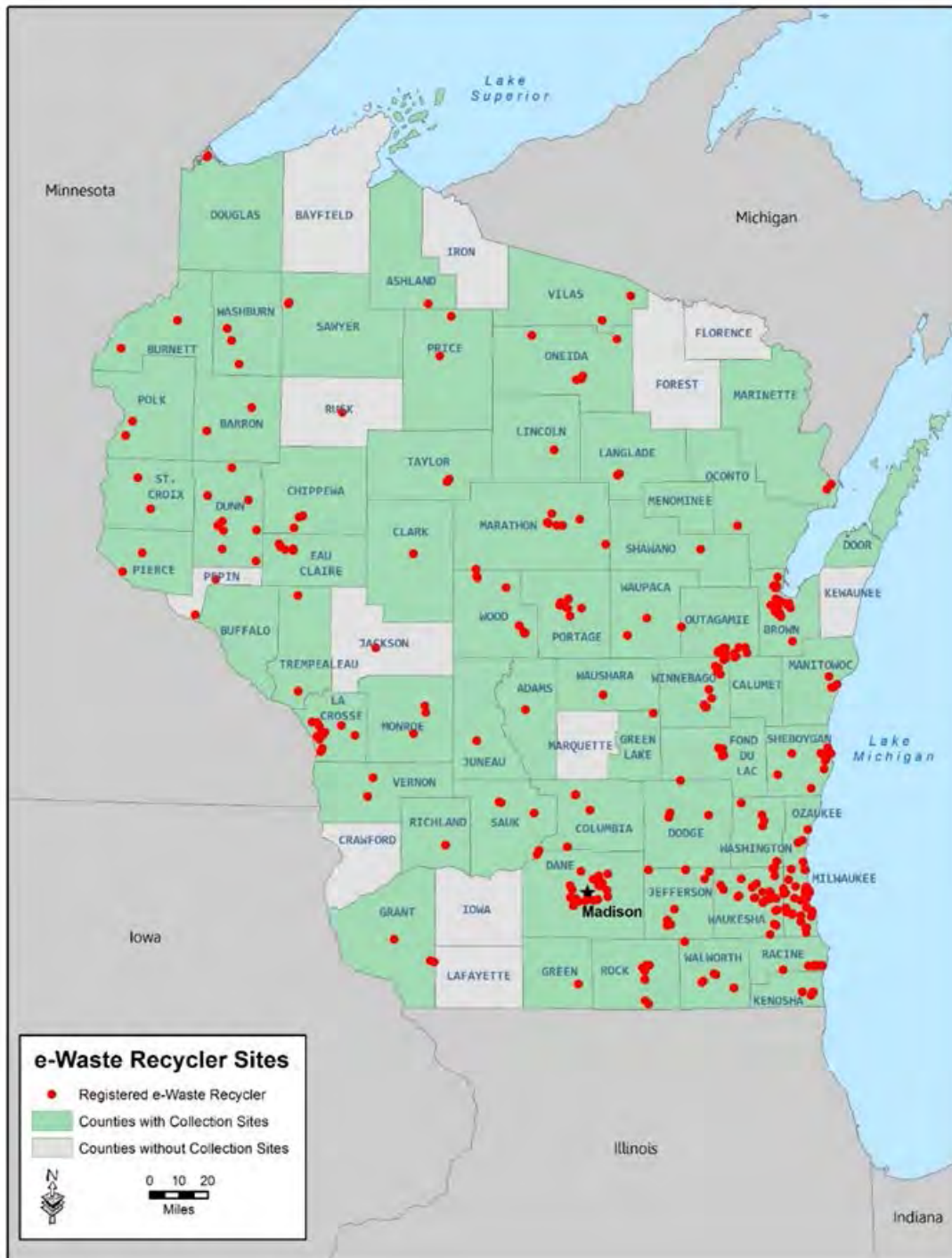
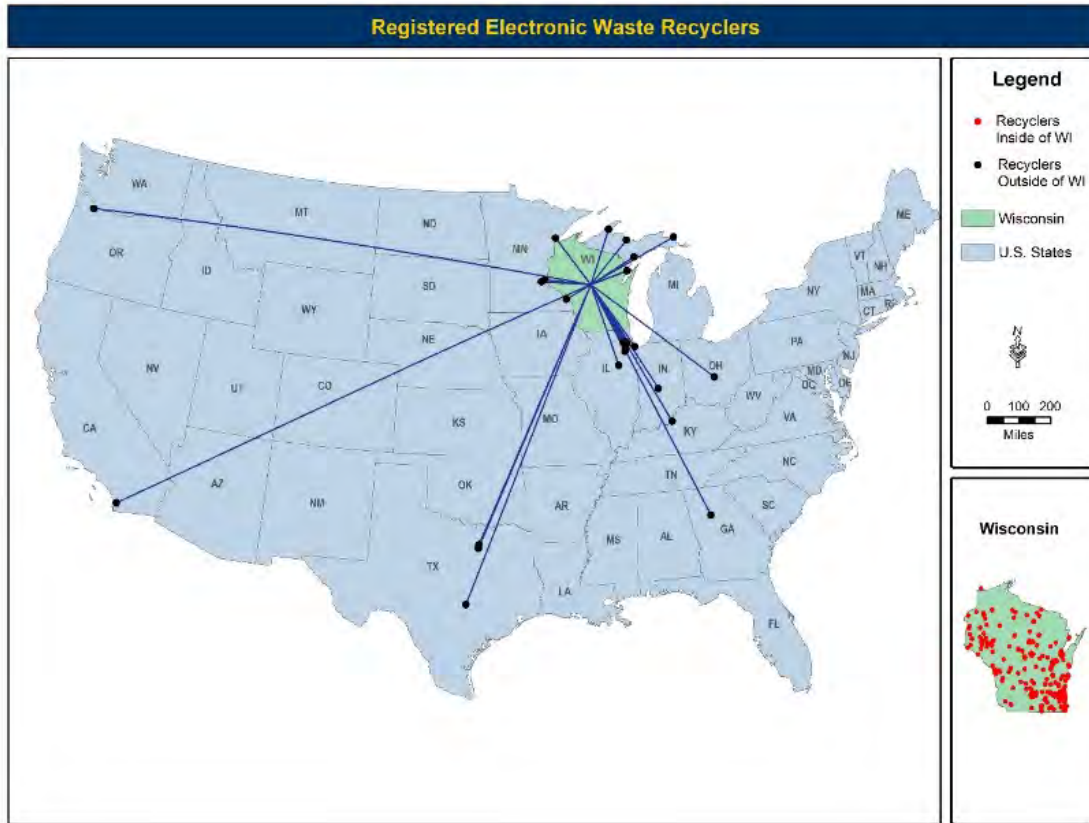


Figure A-9. Recycling Facilities Registered Under E-Cycle Wisconsin Located Outside of Wisconsin (as of July)



A.6 Annual Reports from Registered Entities and State Program Evaluation Reports

All state electronic waste recycling programs require manufacturers to report the weight of CEDs collected or recycled on their behalf in an annual report submitted to the state program tasked with implementing and enforcing each state's rule. Table A-8 summarizes the specific annual reporting requirements for the states evaluated here.

Table A-8. Reporting Requirements for Entities Subject to State E-waste Laws

State	Facility Annual Reporting Requirements
IL	<p><u>Manufacturers:</u></p> <p>Manufacturers are required to submit an annual report to the Illinois Environmental Protection Agency (IEPA) that includes the total weight in pounds of CEDs and EEDs recycled and collected or processed for reuse (monitors, computers, printers, fax machines, scanners called out separately from other CEDs, others are 'remaining CEDs'); the identification of all weights adjusted (e.g., items for donation that get 3× credit); a list of each recycler, refurbisher, and collector used by the manufacturer to fulfill their goal; and a summary of the manufacturer's consumer education program.</p>
IN	<p><u>Manufacturers:</u></p> <p>Due by June of each year. Manufacturers are required to submit a report to the Indiana Department of Environmental Management (IDEM) that includes an estimate of the total weight in pounds of video display devices sold to households by the manufacturer during the program year; the total weight in pounds of CEDs the manufacturer collected from eligible entities and recycled or arranged to have collected from eligible entities and recycled during the program year; and a count of the number of recycling credits held, sold, or to be used by the manufacturer during the program year. Manufacturers may not use credits to meet more than 25% of their annual goals.</p> <p><u>Collectors:</u></p> <p>Collectors are required to report the total weight in pounds of CEDs collected in Indiana by the collector and a list of all recyclers to whom the collector delivered CEDs.</p> <p><u>Recyclers:</u></p> <p>Recyclers are obligated to submit an annual report outlining the total weight in pounds of CEDs recycled by the recycler and taken by the recycler for final disposal during the immediately preceding calendar year, a list of all collectors from whom the recycler received CEDs, and a certification that the recycler has complied with the e-waste law.</p>
MI	<p><u>Manufacturers:</u></p> <p>At the beginning of each fiscal year, manufacturers are required to provide the total weight of CEDs received by the takeback program in the previous year to the Michigan Department of Environmental Quality (MI DEQ).</p> <p><u>Recyclers:</u></p> <p>Recyclers must report the total weight of CEDs recycled during the previous state fiscal year.</p>

(continued)

Table A-8. Reporting Requirements for Entities Subject to State E-waste Laws (continued)

State	Facility Annual Reporting Requirements
MN	<p><u>Manufacturers:</u></p> <p>By September of each year, manufacturers are required to submit a report to the Minnesota Pollution Control Agency (MPCA) that contains the total weight of each specific model of its video display devices sold to households during the previous program year. The manufacturer must also report the total weight of CEDs the manufacturer collected from households and recycled or arranged to have collected and recycled during the preceding program year. Manufacturers must separately report the total weight of CEDs collected from households outside of the 11-county metropolitan area if they wish to receive 1.5× credit for these counties (deemed rural). Manufacturers must also specify the number of recycling credits they have purchased and sold during the preceding calendar year, the number of recycling credits the manufacturer elects to use in the calculation of its variable recycling fee, and the number of recycling credits remaining in its possession. Manufacturers cannot use credits to meet more than 25% of their annual goal.</p> <p><u>Collectors:</u></p> <p>Collectors must separately report the total pounds of CEDs collected in the 11-county metropolitan area and those counties outside of the designated metropolitan area, and a list of all recycler to whom collectors delivered CEDs.</p> <p><u>Recyclers:</u></p> <p>Recyclers of CEDs are required to report the total weight of CEDs recycled during the previous program year and must certify that they comply with all applicable EHS and financial responsibility regulations, are licensed by all applicable government entities, use no prison labor to recycle video display devices, and possess liability insurance of not less than \$1,000,000 for environmental releases, accidents, and other emergencies.</p>
WI	<p><u>Manufacturers:</u></p> <p>Must separately report the total weight of EEDs collected from households or schools in rural counties and those from urban counties in a given program year. The weight is determined by adding the weight used by households or K–12 public schools in urban counties in that program year and 1.25× the weight used by households or K–12 public schools in rural counties in that program year.</p> <p>Must report the total weight of EEDs from households and public K–12 schools that were collected by, or delivered to the manufacturer for recycling by the manufacturer, or that were collected by, or delivered to a registered recycler for recycling on behalf of the manufacturer during the last two program quarters of the preceding year. Manufacturers must report separately the weight of EEDs used by households or schools in rural counties and used by households or schools in urban counties for the purpose of obtaining the weight adjustment/credit for collecting in rural areas.</p> <p>Must also report the credits that the manufacturer has purchased during the preceding program year, the number of credits sold during the preceding program year, the number of credits the manufacturer elects to use in its calculation of its shortfall fees in any given program year, and the number of available credits remaining to the manufacturer. Manufacturers may not use credits to meet more than 20% of their annual goals.</p> <p><u>Collectors:</u></p> <p>Must submit an annual report that details the total weight of EEDs collected in the state during the preceding program year and the names of all registered recyclers to whom the collector delivered EEDs. Collectors may not use prison labor to collect EEDs.</p> <p><u>Recyclers:</u></p> <p>Must submit an annual report that details the total weight of EEDs collected in the state for recycling on behalf of a manufacturer during the first 6 months of the program year and the name of the manufacturer as well as the total weight of EEDs collected in the state that the recycler received for recycling during the first 6 months of the program year in anticipation of attributing them to a manufacturer for the purpose of the program.</p>

The individual annual reports are reviewed, aggregated, and analyzed by the state program staff, who are also required to prepare a report on the previous program year to the legislature or governor (depending on each state's rule requirements). The aggregated reports are publicly available on the programs' Web sites. Table A-9 provides a high-level summary of the key information included in each state's annual report. Michigan is the only state that does not prepare an annual program evaluation report, and the remaining four states prepare reports that are somewhat similar in content and level of detail. The unique and more informative sections of each state's report with respect to material flows are bolded. For example, Illinois and Wisconsin provided estimates of the total amount recycled by product type, although the methods these quantities were assessed are not described. Indiana reports on the quantity of electronics recycled inside and outside the state. Minnesota includes sections on the statewide collection by source (curbside, event, permanent location, pick-up services, and other) and on consistency between other state programs.

Table A-9. Key Information Included in the State E-waste Program Reports

State	State Program Report to the Legislature Available Online?	Key Information Included in State Program Report
IL	✓	<ul style="list-style-type: none"> ▪ Summary of the law ▪ List of CEDs and EEDs ▪ \$2,000 grant recipients ▪ Summary of compliance and enforcement activities (number of manufacturers that failed to meet program goals and/or requirements) ▪ Total pounds recycled across all program years ▪ Total pounds collected from urban and rural counties ▪ Assigned goals and amount recycled by manufacturer ▪ Total amount collected by manufacturers by CED and EED ▪ Total amount of residential e-waste collected by collection site by CED and EED

(continued)

Table A-9. Key Information Included in the State E-waste Program Reports (continued)

State	State Program Report to the Legislature Available Online?	Key Information Included in State Program Report
IN	✓	<ul style="list-style-type: none"> ▪ Summary of the law ▪ List of CEDs ▪ Definition of covered entities ▪ Program participation showing number of registered manufacturers and registered brands ▪ Geographical representation of counties with registered collection sites ▪ Number of annual reports received and a summary of those that met or exceeded their goal and those that did not meet their goal across program years ▪ Total pounds collected as reported by manufacturers and recycled at in- and out-of-state facilities and by metropolitan and nonmetropolitan counties ▪ Total credits earned, used, expired, etc. ▪ Total pounds recycled as reported by recyclers and recycled at in- and out-of-state facilities and by metro and nonmetropolitan counties ▪ Summary of compliance and enforcement activities and policy recommendations
MI	X	<ul style="list-style-type: none"> ▪ The department must submit a report (approximately 2 pages) to the secretary of the senate and to the clerk of the House of Representatives that assesses the adequacy of the fees and any departmental recommendation to modify those fees ▪ No annual report to the legislature on program evaluation is required ▪ By April 1, 2012, the Electronic Waste Advisory Council was to have submitted a report to the governor, the department, and the standing committees of the legislature with jurisdiction over issues primarily pertaining to natural resources and the environment. The report was to evaluate the program under this part and make recommendations to improve the recycling of CEDs; however, it appears the council never met (MRC, 2012).

(continued)

Table A-9. Key Information Included in the State E-waste Program Reports (continued)

State	State Program Report to the Legislature Available Online?	Key Information Included in State Program Report
MN	✓	<ul style="list-style-type: none"> ▪ Summary of the law ▪ Total pounds collected from metro and non-metro counties ▪ Total pounds recycled and credits by program year ▪ Number of registered collectors ▪ Statewide collection by source (curbside, event, permanent location, pick-up services, and other) ▪ Recycling and transportation costs for select counties ▪ Summary of grant awardees ▪ Summary of compliance and enforcement activities ▪ Summary of MPCA activity to promote consistency with other states' programs ▪ Recommendations for legislative consideration
WI	✓	<ul style="list-style-type: none"> ▪ Summary of the law ▪ Summary of program participation across program years for collectors, recyclers, manufacturers, and brands ▪ Collection sites by type (for-profit, retailer, nonprofit, government, and for-profit/government) ▪ Description of the fees charged by registered collector ▪ Total pounds recycled from urban and rural areas ▪ Percentage of weight collected by product type (TVs, computer monitors, computers, other EEDs) ▪ Summary of compliance and enforcement activities ▪ Summary of inspection activities ▪ Compliance and outreach activities related to the disposal ban and illegal dumping ▪ Program success and challenges ▪ Recommendations for legislative consideration

A-7 Compliance and Enforcement

Varying levels of shortfall fees and penalties are imposed on program participants (manufacturers, collectors, recyclers, retailers) for not meeting their yearly goals, or for violating specific requirements outlined by state e-waste laws. The most common penalties incurred by participants are shortfall fees. When manufacturers fail to meet their recycling goal for the current program year, they are required to pay a fee to the implementing

agency. Other penalties for violating specific articles in the program's directorate include a manufacturer's failure to submit an annual registration, a retailer's failure to remove CEDs of an unregistered manufacturer from their shelves in a timely manner, or a recycler's failure to have a certain amount of liability insurance for their operations in the state.

Table A-10 outlines how the selected states calculate shortfall fees for manufacturer targets and handle additional violations of their program code.

Table A-10. Fees and Penalties for Noncompliance with State Programs

State	Shortfall Fees?	Calculation Method for Shortfall Fee	Additional Penalties for Rule Violations?	Penalty Amounts
IL	Yes	Non-tiered	Yes	<ul style="list-style-type: none"> Any person violating any provision of the program pays \$7,000 for the violation and an additional civil penalty not to exceed \$1,000 for each day the violation continues. Manufacturers that do not register but are required to do so by the program are liable for a civil penalty not to exceed \$10,000 for the violation and an additional civil penalty of \$1,000 for each day the violation continues. Recyclers and refurbishers in violation of the rule are liable for a civil penalty not to exceed \$5,000 for the violation. A knowing violation of the landfill ban by anyone other than a residential consumer is a petty offense punishable by a fine of \$500. Residential consumers can be fined a petty offense of \$25 for the first violation and \$50 for subsequent violations.
IN	Yes	Tiered	No	N/A
MI	No	N/A	No	N/A
MN	Yes	Tiered	No	N/A
WI	Yes	Tiered	Yes	<ul style="list-style-type: none"> Any manufacturer who violates the program rules may be required to forfeit not more than \$10,000 for each violation. Any person, other than a manufacturer, who violates the program's rules may be required to forfeit not more than \$1,000 for each violation.

Note: N/A = Not applicable.

Michigan is the only state in the selected states with an e-waste recycling program that does not charge its registrants with any type of penalty for failing to meet numerical goals or for violating any provisions detailed in the program legislation. This lack of fees and penalties may be tied to its limited span of CEDs (manufacturers of computers and manufacturers of video display devices) compared to other states.

Of the four states that charge shortfall fees (also referred to as variable recycling fees) to manufacturers who fail to meet their program year goals, three—Minnesota, Indiana, and Wisconsin—implement a tiered fee structure where manufacturers are charged less per uncollected pound if their total collection is close to their target for that program year.

Appendix B: Supporting Data and Documentation for the Material Flows Analysis

This appendix provides additional information on the development of the material flows analysis (MFA). Section B-1 briefly describes the five methods that have been used to estimate used electronics flows. Section B-2 presents excerpts from a literature review conducted in support of this report that specifically focused on methods to track used electronics flows in the United States. Section B-3 provides specific data from this literature that have been incorporated into the used electronics flow model discussed in Section 3 of this report.

B.1. Overview of the Five Methods Based on the MFA Concept

There are five methods based on the MFA concept: direct sales to e-waste, time step, market supply, consumption and use, and sales obsolescence and transboundary flows. Table B-1 presents the data requirements, advantages, and disadvantages of these methods.

B.1.1. Direct Sales to E-Waste Method

The direct sales to e-waste method is a simplified methodology that assumes the quantity of e-waste generated in a given year is equivalent to the sales in that year; the flows of the e-waste past generation are not considered. This method assumes a saturated market and that with the sale of a new item, an old similar item is disposed of. This method is mathematically represented by Equation B-1.

$$\text{e-waste generation (t)} = \text{sales (t)} \quad \textbf{EQ. B-1}$$

B.1.2. Time Step Method

The time step method uses private and industrial stock and sales data to calculate the quantity of e-waste generated and is mathematically described by Equation B-2 (UNEP, 2009). The e-waste potential during collection phase at time t is calculated from the difference in stock levels of private and industrial equipment during the consumption phase in the period between two points in time (t and $t-1$) plus the sales in that period minus the annual waste produced in that period up to time $t-1$.

$$\text{e-waste generation (t)} = [\text{Stock}(t_1) - \text{Stock}(t)]_{\text{private}} + [\text{Stock}(t_1) - \text{Stock}(t)]_{\text{industry}} + \text{Sales}(n) - \text{e-waste (n)} \quad \text{EQ. B-2}$$

Where:

$\text{Stock}_{\text{private}} = \text{Number of households} \times \text{saturation level of households} / 100$
 $= \text{Population} / \text{average household size} \times \text{saturation of households} / 100$
 $\text{Stock}_{\text{industry}} = \text{number of work places} \times \text{saturation in the industry} / 100$
 $= \text{number of employees} / \text{number of users per appliance}$
 $\text{Sales} = \text{the sales of the equipment considered}$
 $\text{E-waste} = \text{the amount of e-waste produced in the period.}$

B.1.3. Consumption and Use Method

The consumption and use method estimates the amount of e-waste generated using stock and average life span data. The stock is the difference in products manufactured in a given year and the quantity of products sold in a given year; products that are stored in a given year are also included in the amount of stock. This method is mathematically represented by Equation B-3 (UNEP, 2007).

$$\text{e-waste generation (t)} = \frac{[\text{Stock}_{\text{private}}(t) + \text{Stock}_{\text{industry}}(t)]}{\text{Average Lifetime}} \quad \text{EQ. B-3}$$

Where:

$\text{Stock private} = \text{number of households} \times \text{saturation level of the households} / 100$
 $= \text{Population} / \text{average size of household} \times \text{saturation level of the households} / 100$
 $\text{Stock industry} = \text{number of work places} \times \text{saturation level in the industry} / 100$
 $= \text{number of employees} / \text{number of users per appliance} \times \text{saturation level in the industry} / 100$
 $\text{Average lifetime} = \text{the average life span of a product.}$

B.1.4. Market Supply Method

The market supply method uses sales data and typical life spans of electronic devices. The waste potential during the collection phase at time t is calculated from sales data and information about consumption patterns. Mathematically, the market supply method is described in Equation B-4 (UNEP, 2007).

$$\text{e-waste generation (t)} = \text{sales (t - l}_n\text{)} + \text{reuse (t-l}_s\text{)} \quad \text{EQ. B-4}$$

Where:

$\text{Sales} = \text{Sales of electronic devices in time t}$
 $\text{l}_n = \text{Average life span of new items}$
 $\text{l}_s = \text{Average life span of secondhand (reused) items}$

B.1.5. Sales Obsolescence and Transboundary Flows Method

This method is a variation of the market supply method that is used to calculate the amount of e-waste generated but also considers reuse, recycling, exports, and disposal. E-waste generation is estimated from sales or trade data. Assumptions regarding product life spans (including reuse), recycling, storage, and disposal are used to reflect consumer behavior in the disposition of the products. This method is described by the United Nations Environment Programme (UNEP, 2007) as the Carnegie Mellon Method.¹ Similar, but slightly more complex methods are applied by Baldé et al. (2015) and Duan et al. (2013). This method is mathematically represented by Equation B-5.

$$\text{e-waste (t)} = \sum_{i=0}^{t \leq T} \text{Sales}_t \cdot \left[\left(1 - e^{\left(\frac{T-t}{\beta} \right)^\alpha} \right) - \left(1 - e^{\left(\frac{(T-t)-1}{\beta} \right)^\alpha} \right) \right] \quad \text{EQ. B-5}$$

Where:

- T = Year e-waste is generated
- Sales_t = Industry sales for year t
- t = Year product was sold
- β = Weibull distribution scaling factor
- α = Weibull distribution shape factor

¹ An equation is not shown and the Weibull distribution curve is not specifically called out by UNEP (2007). The U.S. Environmental Protection Agency (EPA, 2011) uses a methodology similar to what is described by UNEP (2007) as the Carnegie Mellon method, but a specific equation is also not presented and discrete product life spans are used instead of the Weibull distribution.

Table B-1. Available MFA Methods to Assess E-Waste Flows and Their Associated Data Needs, Disadvantages, and Advantages

Method Name	Data Needs	Disadvantages	Advantages
Direct Sales to E-Waste Method (UNEP, 2007)	<ul style="list-style-type: none"> Sales data for time t 	<ul style="list-style-type: none"> Only suitable for a fully saturated market where the purchase of a product leads to the same quantity of waste from the old product. Limited application in dynamic and developing markets because a larger portion of sales in these markets goes toward stock and does not initially contribute to the amount of e-waste. This method is unsuitable if the temporary storage or reuse of electronics plays a significant role in consumer behavior. 	<ul style="list-style-type: none"> Suitable for carrying out an initial, simplified assessment. Very limited range of input data required. No historical sales data required.
Time Step Method (UNEP, 2007)	<ul style="list-style-type: none"> Information about domestic sales can be obtained from production, import, and export statistics Appliance stock levels can be ascertained from predetermined saturation levels in the household Industrial stock levels are difficult to obtain and require assumptions 	<ul style="list-style-type: none"> Household saturation levels are based on predetermined stock levels Industrial stock levels are assumed in the calculations Assumption that all the waste electrical and electronic equipment (WEEE)/e-waste generated is collected and transferred to treatment and disposal facility 	<ul style="list-style-type: none"> Calculations can be carried out very easily Method provides good results in a saturated market
Market Supply Method (UNEP, 2007)	<ul style="list-style-type: none"> Information about domestic sales required for this calculation can be obtained from production and export statistics Average life of new and secondhand items; the average life of new goods and secondhand appliances is different 	<ul style="list-style-type: none"> The average life to a large extent is subjective because in most developed countries electrical and electronic equipment is often replaced and disposed of before it reaches its technical end-of-life WEEE/e-waste are often stored for years Assumed that all appliances produced in the same year will be in line for disposal after exactly the average life The assumption that the average variance in life of items of electrical and electronic equipment does not change very much, whereas, in reality, lifetimes may become shorter in the future. Therefore, this method is not especially useful in the calculation of WEEE for a dynamic market where technology and life spans are changing rapidly. 	<ul style="list-style-type: none"> Necessary data need not be very wide-ranging Calculations can be carried out very easily using a simple formula Sales data are derived from official statistics from market research institutes or trade organizations and are of good quality and available for a large number of products

(continued)

Table B-1. Available MFA Methods to Assess E-Waste Flows and Their Associated Data Needs, Disadvantages, and Advantages (continued)

Method Name	Data Needs	Disadvantages	Advantages
Consumption and Use Method (UNEP, 2007)	<ul style="list-style-type: none"> Stock data Average life spans by product 	<ul style="list-style-type: none"> A product's constant mean life span is assumed in this method Suitable for estimating WEEE in widely saturated markets with no major deviations from the mean life span, which is a subjective variable 	<ul style="list-style-type: none"> Particularly useful when reliable stock data for an appliance are available
Sales Obsolescence and Transboundary Flows Method (Baldé et al., 2014; Duan et al., 2013; EPA, 2011; UNEP, 2007)	<ul style="list-style-type: none"> Sales data or trade data Export data (new and/or used products) Assumptions about the quantity of products reused Assumptions about the quantity of products stored Assumptions about the quantity of products recycled Assumptions about the quantity of products disposed of in the municipal waste stream (landfilled or incinerated) 	<ul style="list-style-type: none"> Assumptions are made regarding the pathways or material flow during reuse, storage, recycling and landfilling. These assumptions are both product and country specific and therefore demand good knowledge of consumer behavior and the disposal position. Requires a full coverage of sales data as early as possible in the WEEE/e-waste trade value chain. 	<ul style="list-style-type: none"> Allows for an electrical and electronic equipment to be purchased, reused, stored, and recycled or landfilled representing material flow more precisely. Ideal for more extensive examination of individual products. Because of the larger amount of input data, the calculation of WEEE is clearly more extensively structured.

B.2. Excerpts from the MFA Literature Review

This section discusses various approaches to gain an understanding of the flows of used electronics in the past decade.

B.2.1. Stakeholder Workshop Results to Characterize Transboundary Flows of Used Electronics

A stakeholder workshop was held in 2011 to discuss various approaches to characterize transboundary flows of used electronics as part of the efforts to compile the StEP Initiative- and an EPA-funded report entitled *Characterizing Transboundary Flows of Used Electronics* (Miller et al., 2012). A matrix of the workshop's summary results is presented in Tables B-2 and B-3. These tables break down the previously used approaches, newly proposed approaches, and other relevant approaches to characterize flows. These tables are comprehensive, well informed, and based on expert knowledge/opinion from stakeholders in this field. Additional detail on the specific approaches can be found in Miller et al. (2012). In short, the authors note that several approaches should be undertaken simultaneously to

comprehensively characterize flows of used electronics (Miller et al., 2012); the trade-off between the level of effort and quality will also weigh heavily on how an MFA is carried out.

Table B-2. Summary Matrix of Effort Required and Quality of Information for Approaches Identified Through a Stakeholder Workshop Held in 2011 (Miller et al., 2012)

		Effort Required		
		Low	Moderate	Significant
Quality of Information	Low	<ul style="list-style-type: none"> Proxy Trade Data Trade Data 		
	Moderate	<ul style="list-style-type: none"> Enforcement Data: Mandatory Reporting State-Level Data Expand Monitoring of Internet Trading 	<ul style="list-style-type: none"> Enforcement Data: Seizures Handler Surveys Mass Balance Bill of Lading Data Updated Trade Data 	
	Medium-High		<ul style="list-style-type: none"> Voluntary Exports Standards Data Bayesian Truth Serum within Handler Survey Collaboration with Original Equipment Manufacturers (OEMs) Qualitative Case Studies 	<ul style="list-style-type: none"> Surveillance from Inspections Mobile Survey of Recyclers in Developing Countries
	High			<ul style="list-style-type: none"> Electronic Tracking Person in the Port Material Flow Monitoring

Table B-3. Summary of Approaches: Relevance, Effort Required, and Information Quality (Miller et al., 2012)

	Approach	Quantitative	Qualitative			Effort Required	Information Quality
			Business Models	Transactions	Financial Motivations		
Previously Established Approaches	Proxy Trade Data	✓				Low	Low
	Enforcement Data: Mandatory Reporting	✓				Low	Medium
	Enforcement Data: Reporting & Seizure	✓				Low & Moderate	Medium
	Handler Surveys	✓	✓	✓	✓	Moderate	Medium
	Trade Data	✓				Low	Low
	Mass Balance	✓				Moderate	Medium
	Electronic Tracking			✓		Significant	High
Newly Proposed Approaches	Qualitative Case Studies		✓	✓	✓	Moderate	Medium-High
	Person in the Port			✓		Significant	High
	Bill of Lading Data	✓	✓	✓		Moderate	Medium
	State-Level Data	✓			✓	Low	Medium
	Updated Trade Data	✓			✓	Moderate	Medium
	Surveillance from Inspections			✓		Significant	Medium-High
	Voluntary Exports Standards Data	✓	✓	✓	✓	Moderate	Medium-High
	Collaboration with Int'l Agencies	✓				Unknown	Unknown
Additional Approaches	Collaboration with OEMs	✓		✓		Moderate	Medium-High
	Expansion of Monitoring of Internet Trading	✓		✓	✓	Low	Medium
	Mobile Survey of Int'l Recyclers			✓		Significant	Medium-High
	Bayesian Truth Serum Surveys	✓	✓	✓	✓	Moderate	Medium-High
	Material Flow Monitoring	✓		✓		Significant	High

B.2.2. Summary of Key Reports Documenting Electronics Flows Using the MFA Concept

Most documents reviewed (specifically Breivek et al., 2014; Duan et al., 2013; Huisman et al., 2012; Muller et al., 2009; and Zumbuehl, 2006) use the sales obsolescence and transboundary flows method to estimate quantities of used electronics and their disposition. This general approach includes the following steps:

- determine the sales of a product in a region over a period;
- determine an average life span, or a distribution of obsolescence rates;
- calculate the number of products that are predicted to become obsolete in a given year;
- apply a collection fraction to estimate the collected products;
- determine the average weight of the product in each year; and
- multiply by quantity to get total estimated weight generated and collected.

Three groups of researchers/organizations have applied methodologies based on sales data to assess the material flows for multiple product types at a regional, national, or international scale. Table B-4 compares the scope of the products and time series considered (which informs the complexity of the analysis) and the general methodology used at each stage in the product's life cycle across these three research groups. The product scope varies across the references included in Table B-4, as does the time series; this increases the complexity of the MFA because there are more products to track, but does not have a large effect on the methodological approach used other than increasing its complexity.

Table B-5 presents a high-level summary of the methodology used by three key research groups. Note that EPA (2011) does not consider exports. Duan et al. (2013) do consider exports, but only exports of whole units (presumably for reuse). Baldé et al. (2014) quantifies the quantity of e-waste generated by country/region, and does not expand the flows analysis to the amount recycled and exported (or imported for recycling and reuse) by country.

Table B-4. Product Coverage, Geography, and Time Series Across EPA (2011), Duan et al. (2013), and Baldé et al. (2014)

Reference	Product Scope	Geography	Time Series
EPA, 2011	<ul style="list-style-type: none"> ▪ Personal computers: desktop central processing units, portables ▪ Computer displays: cathode ray tube (CRT) monitors and flat-panel monitors ▪ Computer peripherals: keyboards and mice ▪ Hard-copy devices: printers, fax machines, scanners, digital copiers, and multifunction devices ▪ Televisions: monochrome, CRT, flat panel and projection ▪ Mobile devices: cell phones, personal digital assistants (PDAs), smartphones, and pagers 	<ul style="list-style-type: none"> ▪ U.S. 	1980 to 2010
Duan et al., 2013	<ul style="list-style-type: none"> ▪ CRT TVs (and parts) ▪ Flat-panel TVs ▪ Mobile phones ▪ Computers (laptop, desktop) ▪ CRT monitors ▪ Flat-panel monitors 	<ul style="list-style-type: none"> ▪ U.S. ▪ International exports 	2010
Baldé et al., 2014 and 2015	<ul style="list-style-type: none"> ▪ 260 products grouped into 54 product categories as obtained from the Harmonized Commodity Description and Coding System 	<ul style="list-style-type: none"> ▪ Global, by world region 	1995 to 2012

Table B-5. Material Flows Boundaries and Processes Included in EPA, 2011; Duan et al., 2013; and Baldé et al., 2014/2015

Ref	Production/ Sales	Generation	Collection	Recycling	Reuse/ Refurbishment	Disposal	Exports
EPA, 2011	Uses the number of products shipped by model year for each type of product Assumes shipment data are equivalent to sales data, so imports are incorporated	Uses a typical weight for each product type; weights change over time Distinguishes between residential and commercial sales for product categories Uses a typical life span by product type; life span changes over time Uses data from literature and industry experts to determine storage times between residential and commercial	Calculates total weights collected from residential and commercial share based on the life span by product and time spent in storage; used data from states with e-waste legislation (up to 2007)	Uses reported data for states with e-waste legislation (up to 2007); for states without legislation, assumes 1 pound collected and recycled per capita for residential share, and 67% of the quantity collected for recycling from commercial sources	Uses surveys of general e-waste recyclers and mobile device recyclers informed the percentages reused or refurbished	Uses surveys of general e-waste recyclers and mobile device recyclers informed the percentage disposed	Did not include
Duan et al., 2013	Determines the sales of a product in a region over a period	Uses a sales obsolescence approach to determine sales of products to residential and commercial sources Determines the typical distribution of life spans for the product over a time series using two methods: literature-based and survey-based.	Calculates how many products are predicted to be collected in a given year by applying collection rates. Calculates the weight of generated and collected products by multiplying unit weights by the quantities. Uses a distribution of unit weights found from empirical collection data for a given year.	Focuses on whole units and did not specifically look into the quantities recycled. Assumes that 66% was collected for reuse or recycling on a unit basis, or 56% on a weight basis.	Assumes items are obsolete after two terms of use. Assumes that 66% was collected for reuse or recycling on a unit basis, or 56% on a weight basis.	Summarizes percent of e-waste disposed by state from statewide municipal solid waste characterization studies (see Table 17 in the respective report)	Uses domestic export trade data, which theoretically captures the exports of goods produced in the United States or were used in the United States. Focuses on whole units for export only.

(continued)

Table B-5. Material Flows Boundaries and Processes Included in EPA, 2011; Duan et al., 2013; and Baldé et al., 2014 / 2015 (continued)

Ref	Production/ Sales	Generation	Collection	Recycling	Reuse/ Refurbishment	Disposal	Exports
Baldé et al., 2014	Uses international trade statistics from the United Nations Comtrade database and relevant codes from the Harmonization System; sales data = imports – exports	Applies life spans using the Weibull distribution Does not appear to specifically take storage and reuse into account	Uses weights as reported through legislation in each country	Does not appear to take this into account	Does not appear to take this into account	Uses disposal rates by region as presented in the literature	Does not appear to take this into account

B.3. Supporting Data for the e-Waste Model and Results

This section presents supporting data obtained in the literature for the e-waste model presented in Section 3 of this report.

B.3.1 Product Sales

The U.S. product sales data used in EPA (2011) across the 1980–2010 time series were the starting point for the electronics considered. Sales data used in the EPA (2011) report for 2008–2010 were extrapolated based on prior year sales data. To supplement this information, sales data were compiled for 2011–2014 for the electronics included within the scope of this report (see Table A-6). Note that CRT computer monitors and TVs, projection TVs, and monochrome TVs are no longer sold in the United States; desktop and portable computer sales have declined since 2010; and tablet computers have emerged as a new category of computer since the EPA (2011) report, with more than 53 million units (or approximately 30,000 mt assuming an average weight of 0.6 kg per tablet) sold in 2014.

Table B-6. U.S. Electronic Sales Data from 2008 to 2014 (million units)

Year	Desktops	Portables	Hard Copy Peripherals	Mice	Keyboards	PC CRTs	PC Flat Panel	Color CRT <19"	Color CRT >19"	Flat-Panel TVs	Color Projection TV	Mono-chrome TV	Cell Phones	Tablet Computer
2008	30.5	34.1	33.1	30.5	38.4	0.1	32.7	0.4	0.9	29.1	1.1	0.0	198.3	0.0
2009	26.3	46.4	29.5	26.3	33.1	0.0	27.2	0.1	0.3	32.1	0.6	0.0	216.1	5.4
2010	23.5	40.4	29.4	23.5	29.6	0.0	27.5	0.0	0.1	33.7	0.3	0.0	235.6	10.8
2011	21.9	35.5	26.2	21.9	27.6	0.0	25.6	0.0	0.0	38.0	0.1	0.0	213.1	26.6
2012	20.3	30.6	23.0	20.3	25.6	0.0	23.7	0.0	0.0	37.5	0.0	0.0	190.5	37.9
2013	18.7	25.7	19.8	18.7	23.6	0.0	21.9	0.0	0.0	34.0	0.0	0.0	168.0	46.6
2014	17.9	24.5	16.6	17.9	22.5	0.0	20.9	0.0	0.0	34.0	0.0	0.0	143.0	53.2

Note: data for years 2008 through 2010 are from EPA (2011). References for years 2011–2014 include Mearian (2014) for flat-panel TVs; Entner (2015) for mobile phones; and Roy (2015) for tablet computers.

B.3.2 Product Weights

An internet search was conducted to calculate average flat panel-TV weights in the United States for the period 2004 to 2014. The Internet search was done to (1) evaluate the differences between EPA (2011 and 2008) and Wang et al. (2013); and (2) evaluate the trend in U.S. flat panel-TV weights since 2010. Calculated average flat panel-TV weights in

the United States increased from 15.7 kg in 2004 to 16.7 kg in 2005, and then decreased steadily to 10.1 kg in 2010, and thereafter remained at approximately 9.5 to 9.9 kg.

Recommended values for flat panel-TV weights across the time series of product sales are broken out into two groups:

- 1998 to 2004: 15.7 kg for the average market share-adjusted flat-panel weight; and
- 2004 to 2014: use the appropriate values for the average market share-adjusted flat-panel weights from Table B-7.

Table B-7. Calculated Average Market-Share-Adjusted Flat Panel-TV Weights for 2004 to 2014.

Year	LED Unit Share ¹	Plasma Unit Share ¹	Average LED Size (inches, diagonal) ²	Average LED Weight (kg) ³	Average Plasma Weight (kg) ⁴	Average Market Share-Adjusted Flat Panel-TV Weight (kg)
2004	0.81	0.19	28	6.2	56.7	15.7
2005	0.79	0.21	30	6.8	53.1	16.7
2006	0.82	0.18	33	7.7	49.9	15.4
2007	0.87	0.13	35	8.4	44.5	13.1
2008	0.88	0.12	35	8.4	43.1	12.6
2009	0.91	0.09	36	8.8	35.8	11.3
2010	0.91	0.09	35	8.4	26.8	10.1
2011	0.92	0.08	35	8.4	25.1	9.7
2012	0.94	0.06	35	8.4	23.4	9.3
2013	0.95	0.05	36	8.8	21.7	9.4
2014	0.98	0.02	38	9.6	20.0	9.8

¹ U.S. plasma share and LED share are assumed to be the same as worldwide plasma ("PDP") and LED ("LCD") shares as reported by NPD DisplayResearch (2014).

² Average LED screen size as reported by CTA (2011).

³ Calculated from the equation: Weight = $1.6723 * e^{0.0429 * \text{size (inches)}}$. The weight value is then multiplied by an additional 1.12, to adjust for the market mix of TV sizes, considering that weight increases exponentially with size.

⁴ Plasma TV weights for 2004 to 2010 as reported by Boggio and Wheelock (2011). Weights then assumed to decline linearly to 20 kg in 2014.

The following strategy was devised to model flat-panel computer models across the time series of product sales:

- 1989 to 2007: use the average weight of 11.2 kg (as presented in EPA, 2008);
- 2008 to 2013: linearly decrease the average weight from 11.2 kg to 4.1 kg in 2014; and
- 2014: use an average weight of 4.1 kg.

B.3.3 Product Life Spans

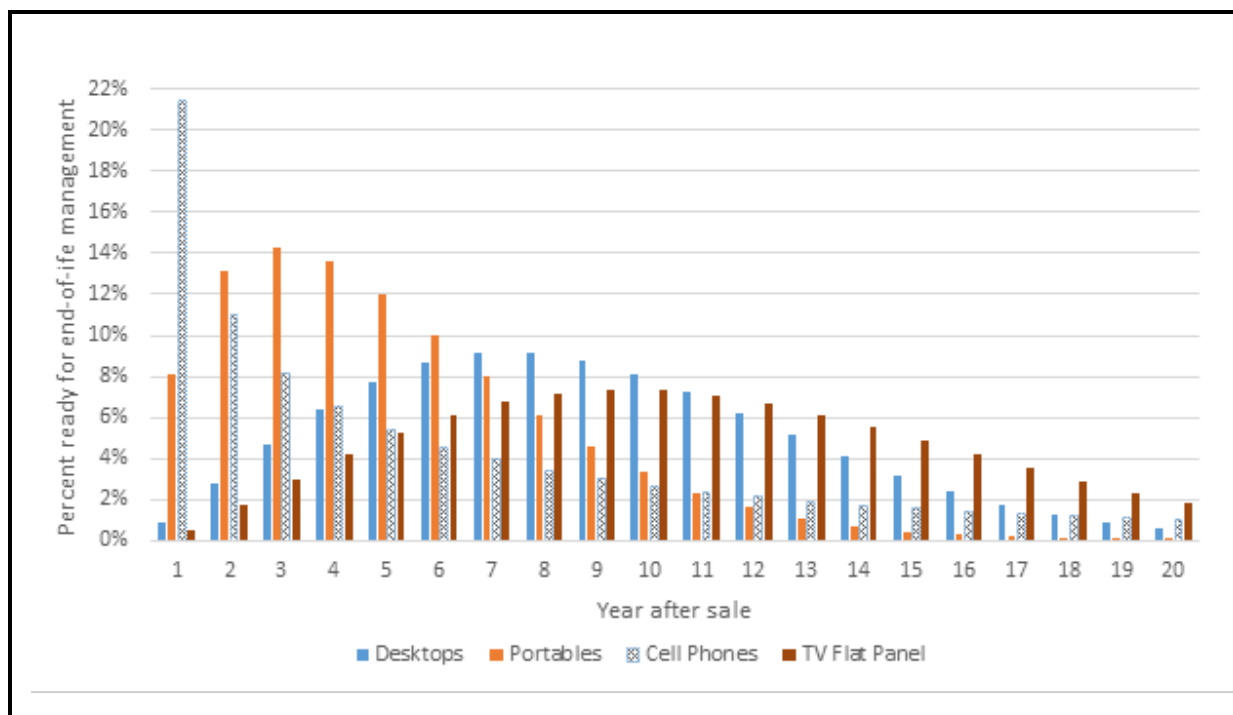
Life span data were reviewed to determine if any changes from the life spans used by EPA (2011) were warranted. Two approaches are used in the literature: discrete product lifetimes and Weibull distributions. Discrete product lifetimes are one value for the life span of each product category (e.g., 20 years for a CRT TV). The Weibull distribution is a continuous probability function that can be used to characterize product life spans.

The primary advantage of a Weibull distribution over a discrete product life span is the continuous nature of the distribution. Additionally, two parameters are used to characterize the distribution—similar to how the slope and the y-intercept are used to characterize a straight line. The two parameters that characterize the Weibull distribution are the scale and shape. The scale parameter generally correlates with the life span; for example, smaller values of the scale parameter equate to shorter lifetimes. The shape parameter indicates the distribution of a life span; a small value for the shape parameter equates to a larger spread in the life span of a product. Both parameter values are always greater than zero.

Table B-8 presents scale and shape parameters found in the literature for various electronic products. Figure B-1 shows the percentage of each piece of equipment discarded each year after sale. Cell phones and portable computers have very short lifetimes (i.e., smaller scale values), whereas desktop computers and flat-panel TVs tend to have longer lifetimes (i.e., larger scale values). Flat-panel TVs also have a large spread in their lifetimes (i.e., a large shape parameter) compared to the other electronic products included in Table B-8.

Table B-8. Weibull Distribution Characterization Parameters in Year 2005 for Various Electronic Products (Wang et al., 2013)

Electronic Product	Shape (α)	Scale (β)
Desktop computer (residential)	2.1	9.6
Portable computer (residential)	1.5	5.2
Cell phone	0.7	7.6
Flat-panel TV	2.1	12.6

Figure B-1. Percentage of Electronic Products Ready for End-of-Life Management After Each Year of Sale (Wang et al., 2013)

Wang et al. (2013) and Baldé et al. (2015) use Weibull distribution values for equipment sold in 1995 and 2005. The values for the shape and scale are similar to those found in Duan et al. (2013) for desktops and CRT monitors. However, the scale parameter (characteristic lifetime) for portables and flat-panel monitors in Wang et al. (2013) are 5.2 years and 7.5 years, respectively, versus values of 13.28 years and 15.05 years, respectively, in Duan et al. (2013).

Weibull distributions are not used in the methodology presented by EPA (2011 or 2008); instead, product life spans are presented as discrete values. For example, 20 percent of residential portable computers are estimated to reach their end-of-life in 4 years, 35 percent in 5 years, 55 percent in 6 years, and 100 percent in 7 years. However, these discrete lifetime values can be converted into approximate Weibull distribution values. For example, the characteristic shape and scale values for residential portable computer lifetimes in EPA 2011 are approximately 5.2 and 6.0, respectively.

Table B-9 presents the approximate Weibull distribution values represented by the discrete lifetime data presented in by EPA (2011) compared to Wang et al. (2013) for select electronic devices. Converting the discrete lifetime data found by EPA (2011) to Weibull distribution values generally yields values similar to those found in Wang et al. (2013) and

Duan et al. (2013). In particular, the scale values are similar, indicating similar product lifetimes. This is important, since the Wang et al. (2013) scale values are based on European data and EPA (2011), while Duan et al. (2013) scale values are based on U.S. data. The similarity in scale values indicates a similar length of product life for European and U.S. electronics. However, the shape parameters tend to be higher in EPA (2011), indicating a narrower distribution in product lifetimes. For example, EPA (2011) assumes that 100 percent of computer mice and keyboards are discarded in year five of their product lifetimes, 100 percent of projection TVs are discarded in year eight, and 100 percent of flat-panel TVs are discarded in year nine. For the proof-of-concept model presented here, the Weibull distribution values reported by Wang et al. (2013) are used in preference to the Weibull distribution values obtained from conversion of the discrete data reported by EPA (2011). It is more realistic to assume that electronic equipment such as mice and keyboards, projection TVs, and flat-panel TVs have a range of product lifetimes, rather than that 100 percent of products are discarded in a particular year.

Table B-9. Comparison of Weibull Distribution Values in year 2005 between EPA (2011) and Wang et al. (2013)

Electronic Device	Reference	Shape	Scale
Desktop computer (residential)	EPA (2011)	2.1	11
	Wang et al. (2013)	2.1	9.6
Portable computer (residential)	EPA (2011)	5.2	6.0
	Wang et al. (2013)	1.5	5.2
Cell phone	EPA (2011)	3.3	4.6
	Wang et al. (2013)	0.7	7.6
Flat-panel TV	EPA (2011)	30	9.0
	Wang et al. (2013)	2.1	12
Mice and keyboards	EPA (2011)	30	5
	Wang et al. (2013)	1.3	5.9
Projection TV	EPA (2011)	30	8
	Wang et al. (2013)	Not reported	Not reported