ASSESSMENT OF SUSTAINABLE MATERIALS MANAGEMENT APPLICATION IN MINNESOTA

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Approach	Description	Key Finding
Best Target Materials Recycling	Determines which materials to prioritize recycling by ranking their environmental impact	Policy makers should prioritize recycling of paper and metal products because they had the largest impact on decreasing the environmental footprint.
Best Disposal Management	Evaluates whether to strategically dispose of a material via combustion or landfilling	From a GHG emissions perspective most materials should be landfilled because they release less emissions than when combusted. But from an energy perspective most material should be combusted instead of landfilled.
Prioritizing Policy and Technology Approach	Identifies which solid waste policy or technology contributes the most environmental avoidances	Policies related to recycling metals, paper, and plastic products result in a large impact on decreasing the environmental footprint.
Prioritizing Stakeholders	Identifies stakeholders that reduce adverse environmental impact	Stakeholders following SMM have a large potential in reducing the environmental footprint, especially residential stakeholders.
Effective Recycling Rates	Relies on a target baseline year and year-of-interest's environmental footprint. The year-of-interest footprint is converted to an "effective" recycling rate, where effective refers to converting the year-of-interest's environmental footprint to a percentage using the baseline year's target environmental footprint and mass-based recycling rate.	Policy makers can measure their recycling progress using the SMM-based metric, which when compared to the mass-based recycling rate was greater in achieving the hypothetical SMM targets.

2 SUSTAINABLE MATERIALS MANAGEMENT IN FLORIDA

In the previous study, we used Florida's solid waste management data as a case study to evaluate the application of lifecycle-based metrics and SMM. The approach used the MSW data provided in the Florida Department of Environmental Protection (FDEP) annual reports along with the US EPA Waste Reduction (WARM) lifecycle assessment (LCA) model, which uses lifecycle impact (LCI) indicators for greenhouse gas (GHG) emissions and energy use, to quantify the environmental impact (or footprint) of Florida's solid waste management. The approach relied on three components: 1) individual material mass disposition data per person (e.g., tons of newspaper per person recycled, combusted, landfilled) for a baseline year, 2) and for a year-of-interest; 3) and LCI indicators.

The general approach followed that the individual materials' mass disposition data per person were multiplied by LCI conversion factors extracted from WARM to estimate an associated GHG emission and energy use footprint. The WARM (version 14, spreadsheet) provided LCI conversion factors for 54 types of waste and their six management approaches: source reduction, recycling, landfilling, combustion, composting, and anaerobic digestion (ICF International, 2016a). The WARM LCI factors were used in their absolute form and converted a mass of material managed to the GHG emissions and energy use. These two impact categories are typically widely accepted in LCA because the data used to create the conversion factors is abundant and collected from various regions internationally. In WARM, GHG emissions are measured in units of metric tons of carbon dioxide equivalence (tCO2eq.) and energy use is measure in units of million British thermal units (mmBTU) which we converted to megajoules (MJ). Results from WARM can be defined as waste management-based GHG emissions or energy use footprint (or when referring to both called an environmental footprint). For each impact category the results are specific to a material and its management, which means that there is a potential for the GHG emissions or energy use footprint to be contradictory of each other. WARM, and other LCA models alike, give decision makers the ability to choose the impact category most important to them and use it to guide their decision making.

A flow chart is presented in Figure 2-1 that outlined the general Florida-specific methodology. The FDEP annual report provided data on generated and recycled disposition on an individual material basis. However, the data related to disposal (landfilled and combustion) was provided on a mixed MSW basis. Assumptions derived from the mixed MSW data were used to estimate the mass of the individual materials combusted and landfilled, including the ash landfilled and recycled. The individual material mass disposition data were multiplied by their respective WARM LCI factors (represented by the dashed line), then summed to generate an estimated GHG emission and energy use footprint per person (represented by the light-gray shaded box). The environmental footprint was estimated for both the baseline year (2008) and the year-of-interest (2020, which was projected from 2015 data).

To evaluate the application of SMM in Florida, we created five hypothetical SMM scenarios in 2020 (based on 2015 FDEP data) and compared them to two baselines (using 2008 FDEP data) that hypothetically reached a 75% recycling rate. The baselines waste management were altered to correspond to a 75% recycling rate because that was the year that a statewide 75% recycling rate goal was enacted. To measure the progress of the scenario toward the baseline the total GHG emissions and energy use of the five scenarios were compared to the baseline GHG emissions and energy use. Doing this, illustrated what it takes to achieve the baseline's mass-based recycling rate target, and its associated GHG emissions and energy use footprint. This established a 75% mass-based recycling rate target and a GHG emission and energy use footprint target for each baseline. However, instead of a straight comparison of tCO2eq. or MJ, the 2020 footprint was converted to an alternative metric, an LCI-normalized recycling rate. The term normalized referred to adjusting values measured on different scales to a common scale. Where, the adjusted values were the GHG emissions and energy use and they were adjusted to a percentage, the unit used by a recycling rate. Equation 1 described how we adjusted the GHG emissions (in units of tCO2eq.) and the energy use (in units of MJ) to a percentage (%). Figure 2-1 showed the mass data collected (recycled, landfilled, combusted, landfilled & recycled ash) and used as inputs to calculate a baseline year and year-of-interest's environmental impact (in GHG emissions and energy use) and how Equation 1 was used to estimate LCI-normalized recycling rates.

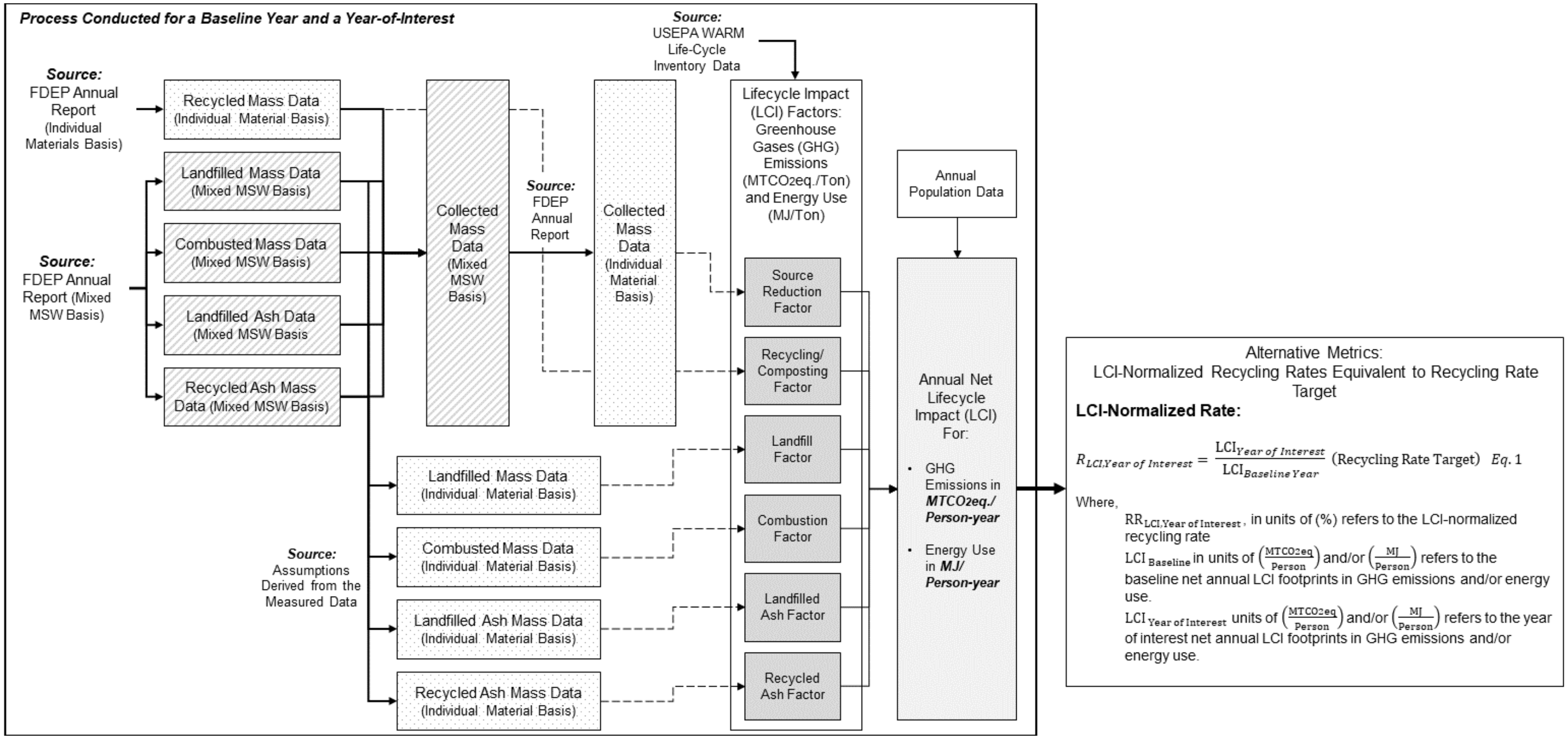
$$\mathrm{R}_{\mathrm{LCI,Year\ of\ Interest}} = \frac{\mathrm{LCI}_{\mathrm{Year\ of\ Interest}}}{\mathrm{LCI}_{\mathrm{Baseline\ Year}}}\,(\mathrm{Recycling\ Rate\ Target}) \qquad \text{Eq. 1}$$

Where,

$\mathrm{R}_{\mathrm{LCI,\ Year\ of\ Interest}}$ refers to the LCI-normalized year-of-interest recycling rate corresponding to the total GHG emissions or energy use.

$\mathrm{LCI}_{\mathrm{Year\ of\ Interest}}$ refers to the total GHG emissions or energy use in the year-of-interest.

$\mathrm{LCI}_{\mathrm{Baseline\ Year}}$ refers to the baseline total GHG emissions or energy use. Multiplying by the target mass-based recycling rate normalizes the results so that the GHG emissions and energy use units are in a percent like the mass-based recycling rate.



Alternative Metrics:
LCI-Normalized Recycling Rates Equivalent to Recycling Rate Target

LCI-Normalized Rate:

$$R_{LCI,Year\ of\ Interest} = \frac{\mathrm{LCI}_{Year\ of\ Interest}}{\mathrm{LCI}_{Baseline\ Year}}\ (\text{Recycling Rate Target}) \quad Eq.\ 1$$

Where,

$\mathrm{RR}_{\mathrm{LCI,Year\ of\ Interest}}$, in units of (%) refers to the LCI-normalized recycling rate

$\mathrm{LCI}_{\mathrm{Baseline}}$ in units of $\left(\frac{\mathrm{MTCO2eq}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ refers to the baseline net annual LCI footprints in GHG emissions and/or energy use.

$\mathrm{LCI}_{\mathrm{Year\ of\ Interest}}$ units of $\left(\frac{\mathrm{MTCO2eq}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ refers to the year of interest net annual LCI footprints in GHG emissions and/or energy use.

Figure 2-1. Florida-specific methodology to estimate mass data (recycled, landfilled, combusted, landfilled & recycled ash) used as inputs to calculate a baseline year and year-of-interest's net lifecycle impact (LCI) (in GHG emissions and energy use) which was converted to an LCI-normalized recycling rate equivalent to a recycling rate target.

3 DATA AVAILABLE FOR MINNESOTA

As previously discussed, the main objective of this study was to evaluate the application of the SMM methodology in other states, specifically MN. To execute the application of the SMM methodology in MN, data was compiled for 2005 and 2015 from the Minnesota Pollution Control Agency (MPCA) published annual reports that detailed waste management data managed by MPCA permitted solid waste acceptance facilities. We assumed that a ten-year time difference was appropriate to measure and track any trends to the waste stream in waste generated more of in 2015 relative to 2005 (referred to as source generated waste) and waste generated less of in 2015 relative to 2005 (referred to as source reduced waste).

For CY 2005 and 2015, the MPCA published two reports: 1) Minnesota Report on SCORE Programs 2005; and 2) Minnesota Report on SCORE Programs 2015. These reports, were used to compile direct data on the total mass generated, managed, recycled, combusted, landfilled, the individual materials recycled mass. The total mass generated and landfilled were modified to remove any imported waste managed by the state, and to account for any waste exported out-of-state for landfill disposal. In 2000 and 2013, the MPCA contracted with R.W. Beck and Burns & McDonnell, respectively, to perform a statewide composition study. The document's findings (see Appendix) were used to estimate indirect data on the individual materials composition and mass landfilled and combusted not provided directly by the MPCA reports or spreadsheets. Whereas, population data needed by the methodology were retrieved from the US Census Bureau website.

Another component required by the methodology was the mass-based recycling rate for the baseline year (2005) and the year-of-interest (2015). Table 3-1 provides detailed information related to the mass-based recycling rate, the mass-based recycling rate targets, and how recycling rates are calculated by the MPCA. Table 3-2 provides the type of data available for MN in 2005 and 2015, and Table 3-3 shows the results of the mass estimates for 2005 and 2015.

There were two recycling rates calculated based on the MPCA provided data, these included: 1) the MPCA recycling rate (without inclusion of additional credits), which included only materials actual recycled at a permitted facility; and 2) the MPCA waste recycling rate (includes additional credits); which included the MPCA recycling rate, yard trash credit, and source reduction credit. The materials included in the MPCA recycling rate were paper, metal, plastic, glass, organics, problem materials, and other materials. The MPCA recycling rate (without inclusion of additional credits) was calculated using Equation 2, whereas, the MPCA recycling rate (includes additional credits) was calculated using Equation 3.

$$\text{MPCA Recycling Rate} = \frac{(\text{recycled mass})}{(\text{recycled mass+landfilled mass+combusted mass})} \text{x } 100 \qquad \text{Eq. 2}$$

$$\text{MPCA Recycling Rate} = \frac{(\text{recycled mass})}{(\text{recycled mass+landfilled mass+combusted mass})} \text{x } 100 + \text{Yard Waste credit} + \text{Source reduction credit} \qquad \text{Eq. 3}$$

Where the yard waste credit specifies that a 3% recycling credit was awarded to a county if a county recycled yard waste. And the source reduction credit was awarded based on the number of source reduction activities accomplished by a county given a set of source reduction activities tracked by the MPCA.

Table 3-1. Recycling information related to recycling rate or waste diversion targets for MN.

	Baseline Year (2005)	Year-of-Interest (2015)	Recycling Rate Target Calculation
Recycling Rate or Waste Diversion Target	50% recycling rate goal by 2011	Minimum 35%to 50% recycling rate goal (depending on county), then 75% recycling rate goal starting in 2030	-
MPCA Recycling Rate (Without Inclusion of Additional Credits)	41%	44%	RR = (Recycled Mass) / (Total Waste Generated) x 100
MPCA Recycling Rate (Includes Additional Credit)	48.5%	44%; note that the MPCA no longer counts yard trash or source reduction credit toward the recycling rate	RR= (Recycled Mass) / (Total Waste Generated) x 100 + Yard Waste Credit + Source Reduction Credit

Table 3-2. Input parameters needed to implement a MN-specific SMM approach. The check mark symbols imply that the Minnesota provides published reports (Arlene Vee and Mark Rust, 2006; Ben Crowell, 2017) or data sets that satisfy the associated data requirement for the baseline year and year of interest.

Data Type	**Baseline Year (2005)**			**Year-of-Interest (2015)**		
	Data Availability	**Associated Mass (Tons)**	**Source**	**Data Availability**	**Associated Mass (Tons)**	**Source**
Population Data*	✓	5,120,000	US Census Bureau	✓	5,483,000	US Census Bureau
MSW Composition Study	n/a	✓, published in 2000	Table 1-7, 2000 Statewide Waste Characterization, Minnesota Pollution Control Agency. R.W. Beck.	✓, published in 2013	-	Table ES-1, 2013 Statewide Waste Characterization, Minnesota Pollution Control Agency. Burns & McDonnell
Total Mixed MSW Data						
Generated	✓	6,085,744	Figure 5, Minnesota Report on SCORE Programs 2005	✓	5,493,966	Table 1, Minnesota Report on SCORE Programs 2015
Managed	✓	6,085,744	Figure 5, Minnesota Report on SCORE Programs 2005	✓	5,493,966	Table 1, Minnesota Report on SCORE Programs 2015
Recycled	✓	2,521,798	Figure 5, Minnesota Report on SCORE Programs 2005	✓	2,397,855	Table 1, Minnesota Report on SCORE Programs 2015
Combusted	✓	1,240,000	Figure 5, Minnesota Report on SCORE Programs 2005	✓	1,296,517	Table 1, Minnesota Report on SCORE Programs 2015
Landfilled	✓	2,320,000	Figure 5, Minnesota Report on SCORE Programs 2005	✓	1,799,594	Table 1, Minnesota Report on SCORE Programs 2015
Recycled Ash	n/a	-		n/a	-	
Ash and By-pass	n/a	-		n/a	-	
Back-End Scrap Metal	n/a	-		n/a	-	
Landfilled Ash	n/a	-		n/a	-	
MSW-ash, back-end scrap metal, & by-pass	n/a	-		n/a	-	
Non-MSW ash & By-pass	n/a	-		n/a	-	
Individual Material Data						
Generated	n/a	n/a		n/a	n/a	
Managed	n/a	n/a		n/a	n/a	
Recycled	✓	See Table A3	Appendix, Minnesota Report on SCORE Programs 2005	✓	See Table A3	Appendix, Minnesota Report on SCORE Programs 2005
Landfilled	n/a	n/a		n/a	n/a	
Combusted	n/a	n/a		n/a	n/a	
Recycled Ash	n/a	n/a		n/a	n/a	
Landfilled Ash	n/a	n/a		n/a	n/a	

*Units in persons.

Table 3-3. 2005 and 2015 individual material mass estimates and associated recycling rates for MN.

		2005				2015				2005	2015
Item No.	Material	Generated (Tons/ Person)	Recycled & Composted (Tons/ Person)	Combusted (Tons/ Person)	Landfilled (Tons/ Person)	Generated (Tons/ Person)	Recycled & Composted (Tons/ Person)	Combusted (Tons/ Person)	Landfilled (Tons/ Person)	Recycling Rate[a]	Recycling Rate[a]
1	Newspaper	0.067	0.039	0.010	0.019	0.032	0.024	0.003	0.005	57.5%	75.6%
2	Glass	0.043	0.023	0.007	0.013	0.036	0.024	0.005	0.007	54.5%	65.5%
3	Aluminum Cans	0.014	0.005	0.003	0.005	0.011	0.005	0.003	0.004	39.1%	42.1%
4	Steel Cans	-	-	-	-	-	-	-	-	-	-
5	Corrugated Paper	0.119	0.071	0.017	0.031	0.097	0.075	0.009	0.013	59.8%	76.8%
6	Plastic Bottles	0.010	0.001	0.003	0.005	0.016	0.003	0.006	0.008	12.3%	16.8%
7	Yard Trash	0.144	0.104	0.014	0.026	0.087	0.044	0.018	0.025	72.0%	51.1%
8	Mixed Plastics	0.079	0.008	0.025	0.046	0.096	0.009	0.037	0.051	10.4%	9.1%
9	Food Waste	0.122	0.035	0.030	0.056	0.161	0.061	0.042	0.058	29.1%	37.7%
10	Mixed Paper	0.232	0.070	0.056	0.106	0.165	0.058	0.045	0.063	30.3%	35.3%
11	Mixed Metals	0.117	0.090	0.009	0.018	0.106	0.087	0.008	0.011	76.9%	82.0%
12	Textiles	0.039	0.003	0.012	0.023	0.042	0.002	0.017	0.023	7.9%	5.5%
13	Tires	0.009	0.003	0.002	0.004	0.006	0.006	-	-	37.6%	-
14	Electronics	0.015	0.001	0.005	0.009	0.010	0.004	0.003	0.004	10.2%	34.5%
15	C&D Debris	0.019	-	0.007	0.013	-	-	-	-	-	-
16	Miscellaneous	0.160	0.037	0.043	0.080	0.134	0.036	0.041	0.057	22.9%	26.9%
	Total	**1.188**	**0.493**[b]	**0.242**	**0.453**	**1.001**	**0.437**[b]	**0.236**	**0.328**	**41.5%**	**43.7%**
	Total (w/o C&D or Misc.)	**1.009**				**0.867**					

Note: The recycled masses are provided by the Minnesota Pollution Control Agency (MPCA) annual solid waste reports. The combusted and landfilled masses were estimated by applying a MPCA statewide disposal waste composition study. Generated mass was calculated as the sum of recycled, combusted, and landfilled. The material categories in the report were re-organized to the 16 material categories but MPCA does not report estimates of certain materials (see Appendix). C&D debris recycled was not reported by MPCA, and for materials with no combusted or landfilled estimates they were not accounted in the waste composition studies. Steel cans recycled were only reported in 2005 and were aggregated into the mixed metals category.

a: Recycling rate was calculated as the recycled & composted mass divided by generated mass.
b: The recycled & composted mass includes all 16 materials

4 EVALUATION OF DATA NEEDS

After compiling all the available data related to MN’s solid waste management, we identified that there were still knowledge gaps. Directly the mass of individual materials generated, landfilled, and combusted for both years were not reported. However, using our methodology we indirectly estimated the mass of individual materials landfilled and combusted by applying the findings of the waste composition studies to the total mass disposed of (landfilled and combusted). Then using those estimates and the reported mass of individual materials recycled we indirectly estimated the mass of individual materials generated as the sum of the individual materials recycled, landfilled, and combusted.

This process to estimate the individual material’s mass balance is possible for MN’s 2005 data because the 2005 report provided the total landfilled and combusted, and individual materials mass recycled, and the 2000 waste composition study provided the composition of the disposal stream. Similarly, the 2015 report provided the total landfilled and combusted masses, and the individual materials recycled masses, and the 2013 waste composition study provided the composition of the disposal stream. Furthermore, the 2005 and 2015 reports did not report the mass or composition of recycled and landfilled ash.

Additional data need concerns were associated with the tracking and reporting of material types. In this analysis we estimated disposition masses for the materials reported by MPCA in the annual reports and for the materials evaluated by the waste composition studies. Because the type of recycled materials tracked and reported differed in 2005 and 2015, we re-organized the suite of recycled material categories so that they are comparable. Similarly, we re-organized the suite of materials evaluated in the 2000 and 2013 waste composition study for simplification. The purpose of this re-organization was to identify a standardized suite of material categories so that an individual category was associated with a recycled, landfilled, and combusted mass to estimate an individual material’s generated mass. It should be noted that some material types were accounted in the recycling disposition but were not accounted in the landfill or combustion dispositions- because they were not evaluated by the composition study or the recycled material was not required to be tracked- and vice versa. Also, the current suite of material includes paper, plastic, metal, glass, organics, other materials, and problem materials, and does not include other materials that may be recycled at high quantities, such as construction and demolition (C&D) debris. All materials re-organization are shown in the Appendix

5 SUSTAINABLE MATERIALS MANAGEMENT IN MINNESOTA

A locSal government may apply SMM using various approaches, this section will focus on five approaches. The first four approaches use SMM to strategically plan and prioritize materials, technology, or policies, they include the following approaches: 1) Best Target Materials Recycling; 2) Best Disposal Management; 3) Prioritizing Policy and Technology; and 4) Prioritizing Stakeholders. The last approach uses SMM to measure the performance or set goals for a solid waste system and will be referred to as the Effective Recycling Rates approach. A description of each approach and their data needs was provided in Table 5-1.

Table 5-1. Description of the five SMM approaches applied to MN.

Approach	Description	Data Needs
Best Target Materials Recycling	Determines which materials to prioritize recycling by ranking their environmental impact	Environmental footprint for a single year-of-interest
Best Disposal Management	Evaluates whether to strategically dispose of a material via combustion or landfilling	Environmental footprint for a single year-of-interest
Prioritizing Policy and Technology Approach	Identifies which solid waste policy or technology contributes the most environmental avoidances	Environmental footprint for a single year-of-interest
Prioritizing Stakeholders	Identifies stakeholders that reduce adverse environmental impact	Environmental footprint for a single year-of-interest
Effective Recycling Rates	Relies on a historic target baseline year and year-of-interest's environmental footprint. The year-of-interest footprint is converted to an "effective" recycling rate, where effective refers to converting the year-of-interest's environmental footprint to a percentage using the baseline year's target environmental footprint and mass-based recycling rate.	Environmental footprint for a historic year and a year-of-interest and

The application of the study's SMM methodology required individual materials mass generation and disposition and their WARM LCI factors to estimate an environmental footprint for a baseline year and year of interest. The materials and their associated WARM material category proxies are shown in Table 5-2. Using the data in Table 3-3, we estimated a net environmental footprint of -1.727 tCO_2eq./person and -18,499 MJ/person associated with MN's 2015 waste management system (including the impacts of waste source reduced and generated in 2015 relative to 2005) and -1.037 tCO_2eq./person and -12,193 MJ/person associated with MN's 2005 waste management system. The total footprint was calculated by summing the footprints associated with source reducing (or generating), recycling, landfilling, and combusting MSW. Each of these footprints were provided on a per person and a total basis in Tables 5-3 and 5-4 for

2005 and 2015. Tables 5-5 and 5-6 showed the material components that were used in Tables 5-3 and 5-4. The negative values indicated that the state's management of waste resulted in an avoidance of GHG emissions and energy due to the large recycling offsetting virgin materials. The environmental footprints are used in the SMM approaches and discussed in the next sections.

Table 5-2. WARM emission and energy factors for MSW materials, based on EPA WARM v14 and for energy use the units are converted from WARM default units of mmBTU/short ton to MJ/short ton.

MSW material	Source Reduction (tCO_2eq./short ton)	Recycled (tCO_2eq./short ton)	Combusted (tCO_2eq./short ton)	Landfilled (tCO_2eq./short ton)	Source Reduction (MJ/short ton)	Recycled (MJ/short ton)	Combusted (MJ/short ton)	Landfilled (MJ/short ton)
Newspaper	-4.77	-2.75	-0.581	-0.823	-38,472	-17,398	-7,948	55
Glass	-0.526	-0.277	0.028	0.020	-7,285	-2,247	526	283
Aluminum Cans	-4.91	-9.11	0.035	0.020	-94,629	-161,170	630	283
Steel Cans[a]	-3.06	-1.81	-1.57	0.020	-31,526	-21069	-18,079	283
Corrugated Paper	-5.60	-3.12	-0.509	0.235	-23,549	-15,900	-7,009	-259
Plastic Bottles[b]	-1.84	-0.993	1.22	0.020	-58,802	-43,294	-15,550	283
Yard Trash[c,d]	n/a	-0.146	-0.175	-0.268	n/a	612	-2,616	125
Mixed Plastic	-1.92	-1.02	1.22	0.020	-57,415	-40,978	-14,384	283
Food Waste[c]	-3.66	-0.176	-0.141	0.543	-15,361	612	-2,171	-25
Mixed Paper	-6.75	-3.53	-0.512	0.127	-31,064	-21,576	-7,036	-218
Mixed Metals[a]	-3.70	-4.34	-1.02	0.020	-53,393	-69,623	-11,596	283
Textiles	-3.82	-2.36	1.08	0.020	-96,078	-22,652	-7,585	283
Tires	-4.28	-0.376	0.506	0.020	-75,659	-3,756	-30,090	283
Electronics	-50.5	-2.50	-0.188	0.020	-1,009,416	-30,759	-6,618	283
C&D Debris[e]	-	-	-	-	-	-	-	-
Miscellaneous[e]	-	-	-	-	-	-	-	-

Note: This assumes WARM defaults, including typical US national average landfill gas collection and recovery for energy and default distance from collection site to landfill/recycling facility of 20 miles.

a. *For steel cans and mixed metals in WARM steel is assumed to be recovered after combustion, but we assumed the associated GHG emissions or energy use avoidance originally included by WARM in the combustion factors were not included in the analysis.*

b. *Emission/energy factors do not exist for plastic bottles in WARM; an average of the WARM categories for HDPE and PET was used as a proxy.*

c. *Recycling emission/energy factors do not exist for organic materials in WARM; composted emission/energy factors were used as a proxy.*

d. *Source reduction emission/energy factors do not exist for yard trash in WARM.*

e. *C&D Debris and miscellaneous materials' GHG emissions and energy use footprints were not assessed in the study.*

Table 5-3. Environmental footprint for recycling, combustion, and landfill for MN in 2005.

Disposition	GHG Emissions (tCO_2eq.)	Energy Use (10,000 MJ)	GHG Emissions (tCO_2eq./Person)	Energy Use (MJ/Person)
Recycling	-5,468,916	-5,611,617	-1.068	-10,960
Combustion	-612	-634,418	0.000	-1,239
Landfill	160,668	3,304	0.031	6
Total Footprint	-5,308,860	-6,242,731	-1.037	-12,193

Note: Tables 5-5 and 5-6 details each materials GHG emissions and energy use per person for 2005.

Table 5-4. Environmental footprint for recycling, combustion, and landfill for MN in 2015.

Disposition	GHG Emissions ($tCO_2eq.$)	Energy Use (10,000 MJ)	GHG Emissions ($tCO_2eq./Person$)	Energy Use (MJ/Person)
Recycling	-5,363,731	-5,661,393	-0.978	-10,325
Combustion	173,902	-703,752	0.032	-1,284
Landfill	189,356	8,394	0.035	15
Source Reduction	-4,550,220	-3,918,205	-0.830	-7,146
Total Footprint	-9,470,713	-10,143,208	-1.727	-18,499
Total Footprint (w/o WP)	-4,920,493	-6,225,003	-0.897	-11,353

Note: Tables 5-5 and 5-6 details each materials GHG emissions and energy use per person for 2015.

Table 5-5. GHG emissions footprint for each material's disposition (i.e., recycling & compositing, combustion, and landfill) for MN in 2005 and 2015.

		2005				2015					
Item No.	Material	Recycling & Composting Emissions (tCO$_2$eq./ Person)	Combustion Emissions (tCO$_2$eq./ Person)	Landfill Emissions (tCO$_2$eq./ Person)	Total Emissions (tCO$_2$eq./ Person)	Recycling & Composting Emissions (tCO$_2$eq./ Person)	Combustion Emissions (tCO$_2$eq./ Person)	Landfill Emissions (tCO$_2$eq./ Person)	Source Reduction (SR) Emissions (tCO$_2$eq./ Person)	Total Emissions with SR (tCO$_2$eq./ Person)	Total Emissions without SR (tCO$_2$eq./ Person)
1	Newspaper	-0.1061	-0.0058	-0.0153	-0.1272	-0.0672	-0.0019	-0.0038	-0.1658	-0.2387	-0.0729
2	Glass	-0.0065	0.0002	0.0003	-0.0060	-0.0065	0.0001	0.0001	-0.0036	-0.0098	-0.0062
3	Aluminum Cans	-0.0487	0.0001	0.0001	-0.0485	-0.0411	0.0001	0.0001	-0.0146	-0.0555	-0.0409
4	Steel Cans	-	-	-	-	-	-	-	-	-	-
5	Corrugated Paper	-0.2226	-0.0085	0.0073	-0.2238	-0.2334	-0.0048	0.0031	-0.1227	-0.3579	-0.2352
6	Plastic Bottles	-0.0012	0.0035	0.0001	0.0025	-0.0027	0.0069	0.0002	0.0124	0.0168	0.0044
7	Yard Trash	-0.0152	-0.0025	-0.0070	-0.0247	-0.0065	-0.0031	-0.0066	0.0000	-0.0162	-0.0162
8	Mixed Plastics	-0.0083	0.0299	0.0009	0.0225	-0.0089	0.0446	0.0010	0.0338	0.0706	0.0367
9	Food Waste	-0.0062	-0.0042	0.0305	0.0201	-0.0107	-0.0059	0.0317	0.1448	0.1599	0.0151
10	Mixed Paper	-0.2489	-0.0289	0.0134	-0.2644	-0.2057	-0.0230	0.0079	-0.4536	-0.6744	-0.2208
11	Mixed Metals[a]	-0.3923	0.0002	0.0004	-0.3917	-0.3789	0.0002	0.0002	-0.0407	-0.4192	-0.3785
12	Textiles	-0.0072	0.0133	0.0005	0.0066	-0.0055	0.0178	0.0005	0.0127	0.0255	0.0128
13	Tires	-	-	-	-	-	-	-	-	-	-
14	Electronics	-0.0037	0.0012	0.0002	-0.0023	-0.0089	0.0008	0.0001	-0.2203	-0.2284	-0.0081
15	C&D Debris[b]	-	-	-	-	-	-	-	-	-	-
16	Miscellaneous[b]	-	-	-	-	-	-	-	-	-	-
	Total	**-1.067**	**-0.001**	**0.031**	**-1.037**	**-0.976**	**0.032**	**0.035**	**-0.818**	**-1.727**	**-0.910**

Note: Each disposition's GHG emissions were calculated by first multiplying each materials' recycling & composted masses found in Table 3-3 (in tons/person) by their respective recycled WARM GHG emissions factors found in Table 5-2. The total for each disposition (e.g., recycling & composting emissions, etc.) are also shown in Tables 5-3 and 5-4.

a. Steel cans and tires mass dispositions (in tons/person) were not estimated and thus the GHG emissions and energy use footprints were not assessed in the study, refer to Table 3-3 for more details.

b. C&D Debris and miscellaneous materials' GHG emissions and energy use footprints were not assessed in the study.

Table 5-6. Energy use footprint for each material's disposition (i.e., recycling & compositing, combustion, landfill, and source reduction) for MN in 2005 and 2015.

Item No.	Material	2005				2015					
		Recycling & Composting Energy Use (MJ/Person)	Combustion Energy Use (MJ/Person)	Landfill Emissions Energy Use (MJ/Person)	Total Energy Use (MJ/ Person)	Recycling & Composting Energy Use (MJ/ Person)	Combustion Energy Use (MJ/Person)	Landfill Energy Use (MJ/ Person)	Source Reduction (SR) Energy Use (MJ/ Person)	Total Energy Use with SR (MJ/Person)	Total Energy Use without SR (MJ/Person)
1	Newspaper	-671.7	-78.92	1.019	-749.6	-425.2	-26.31	0.2520	-1,338	-1,789	-451.3
2	Glass	-52.32	3.569	3.591	-45.16	-52.88	2.738	2.044	-49.51	-97.61	-48.10
3	Aluminum Cans	-862.1	1.831	1.539	-858.7	-727.0	1.638	1.022	-281.1	-1,005	-724.3
4	Steel Cans	-	-	-	-	-	-	-	-	-	-
5	Corrugated Paper	-1,135	-117.1	-8.098	-1,260	-1,190	-66.29	-3.400	-516.4	-1,776	-1,259
6	Plastic Bottles	-50.80	-45.19	1.539	-94.45	-118.1	-88.25	2.230	397.7	193.6	-204.2
7	Yard Trash	63.96	-36.74	3.287	30.50	27.24	-46.39	3.078	0	-16.07	-16.07
8	Mixed Plastics	-334.3	-353.6	13.02	-674.8	-358.0	-527.5	14.41	1,010	138.6	-871.1
9	Food Waste	21.80	-65.19	-1.392	-44.78	37.40	-91.36	-1.447	608.4	553.0	-55.41
10	Mixed Paper	-1,521	-397.0	-23.06	-1,941	-1,257	-316.9	-13.65	-2,088	-3,676	-1,588
11	Mixed Metals[a]	-6,292	5.182	5.002	-6,281	-6,077	4.411	3.159	-587.2	-6,657	-6,070
12	Textiles	-69.09	-93.69	6.541	-156.2	-52.37	-125.6	6.503	319.8	148.4	-171.4
13	Tires	-	-	-	-	-	-	-	-	-	-
14	Electronics	-46.02	-5.972	2.437	-49.55	-109.8	-3.682	1.115	-4,404	-4,516	-112.3
15	C&D Debris[b]	-	-	-	-	-	-	-	-	-	-
16	Miscellaneous[b]	-	-	-	-	-	-	-	-	-	-
	Total	**-10,948**	**-1,183**	**5.427**	**-12,125**	**-10,303**	**-1,284**	**15.31**	**-6,928**	**-18,499**	**-11,571**

Note: Each disposition's GHG emissions were calculated by first multiplying each materials' recycling & composted masses found in Table 3-3 (in tons/person) by their respective recycled WARM GHG emissions factors found in Table 5-2. The total for each disposition (e.g., recycling & composting emissions, etc.) are also shown in Tables 5-3 and 5-4.

a. *Steel cans and tires mass dispositions (in tons/person) were not estimated and thus the GHG emissions and energy use footprints were not assessed in the study, refer to Table 3-3 for more details.*

b. *C&D Debris and miscellaneous materials' GHG emissions and energy use footprints were not assessed in the study.*

5.1 Best Target Materials Recycling Approach

5.1.1 Methodology

The purpose of this approach was to demonstrate how solid waste policy makers can use the SMM model to prioritize which materials to recycle to increase progress towards sustainability by increasing their recycling rate and decreasing their environmental footprint. Materials were ranked by their impact to decrease or increase the GHG emissions and energy use footprint; the following steps were used to rank materials using 2015 mass data (Table 3-4):

→ **Step 1:** For an individual material, its recycled mass was multiplied by 1.05, to represent a hypothetical 5% increase in the recycled mass.

> *Note: We increased the recycled mass to account for potentially available recycled mass; materials with a low recycling rate will generate a larger increased mass than those with high rates. The 5% value was not specific to any policy or regulation.*

→ **Step 2:** For an individual material, the increased recycled mass was removed from its landfilled and combusted masses proportionally. We calculated the decreased landfill mass by multiplying the additional increased recycled mass by a ratio calculated as the initial 2015 landfilled mass divided by the sum of its initial 2015 landfilled. Then, we calculated the decreased combusted mass by multiplying the additional increased recycled mass by a ratio calculated as the initial 2015 combusted mass divided by the sum of its initial 2015 landfilled and combusted masses.

→ **Step 3:** For an individual material, we estimated its environmental footprint using the increased recycled mass, decreased landfilled mass, and decreased combusted masses from Steps 1 and 2 multiplied by their respective WARM GHG emission and energy use factors.

→ **Step 4:** Steps 1 thru 3 were repeated for each and all individual materials.

→ **Step 5:** Materials were ranked from most negative GHG emissions and energy use footprints to least negative value.

5.1.2 Application in Minnesota

Table 5-7 presents the results of the approach, where higher ranked materials signify that increasing their recycled mass resulted in a larger impact in decreasing the footprint, and lower ranked materials resulted in a smaller impact to decreasing the footprint or their recycling resulted in increasing the footprint.

The materials that resulted in the most additional GHG emissions and energy avoidance were corrugated paper, mixed paper, and electronics. WARM assumes that recycled materials replace the use of virgin materials and this offsets emissions/energy associated with extracting, processing, and manufacturing (ICF International, 2016b). In WARM the materials with the greatest GHG emissions and energy avoidances when recycled are metals and paper products because they offset virgin material’s extraction and processing.

The materials ranked the lowest from a GHG emissions perspective was yard trash, and for energy, tires, food waste, and yard trash ranked lowest. Recycled yard trash and food waste are ranked lowest because they are composted, a process energy intensive that requires heavy machinery (ICF International, 2016c). Whereas, recycling tires does offset energy, but the increased recycled mass originating from the combusted mass results in a loss of avoidance because combustion generates more avoidance than recycling (ICF International, 2016d). MN solid waste policy makers can prioritize their efforts to focus on which materials to recycle based off the environmental impacts

Table 5-7. Results of the Best Target Materials Recycling approach applied to MN's waste management in 2015.

	Material		Material
Material Organized by Their Impact to Reduce the 2015 GHG Emissions Footprint (Larger to Smaller)	Mixed Metals	Material Organized by Their Impact to Reduce the 2015 Energy Use Footprint (Larger to Smaller)	Mixed Metals
	Corrugated Paper		Mixed Paper
	Mixed Paper		Corrugated Paper
	Newspaper		Aluminum Cans
	Aluminum Cans		Newspaper
	Food Waste		Mixed Plastics
	Mixed Plastics		Plastic Bottles
	Electronics		Electronics
	Glass		Glass
	Textiles		Textiles
	Plastic Bottles		**Yard Trash**
	Yard Trash		**Food Waste**

Note: Bolded materials are associated with an emission of GHG or an energy usage. And the approach was not applied to C&D debris and Miscellaneous materials.

5.2 Best Disposal Management Approach

5.2.1 Methodology

The current approach to manage materials for disposal is to collect comingled MSW and mass burn or landfill, in this approach we use the SMM model to demonstrate how solid waste policy makers may evaluate which disposal method is most appropriate by comparing the environmental footprint resulting when landfilling or combusting a material. The following steps were used to identify which disposal method resulted in the most GHG emissions and energy use avoidance using 2015 mass data (Table 3-3):

→ **Step 1:** For an individual material, its landfilled mass was multiplied by 1.05, to represent a 5% increase in the landfilled mass.

Note: The 5% value was not specific to any policy or regulation.

→ **Step 2:** For a material, the increased landfilled mass was removed from its combusted masses; the recycled mass was unaltered.

→ **Step 3:** For a material, we estimated an environmental footprint associated with the increased landfilled mass and the decreased combusted mass from Steps 1 and 2 multiplied by their respective WARM GHG emission and energy use factors.

→ **Step 4:** Steps 1 thru 3 were repeated for each individual material. These results will be used in Step 9.

Note: Steps 1 thru 3 correspond to increasing the landfill mass and Steps 5 thru 7 correspond to increasing the combusted mass. We increased the landfilled and *combusted masses each by the same mass increase (5%) to ensure we are evaluating the impacts of landfilling or combusting the same mass.*

→ **Step 5:** For a material, its combusted mass was multiplied by 1.05, to represent a 5% increase in the combusted mass.

Note: The 5% value was not specific to any policy or regulation.

→ **Step 6:** For a material, the increased combusted mass was removed from its landfilled masses; the recycled mass was unaltered.

→ **Step 7:** For a material, we estimated an environmental footprint associated with the decreased landfilled mass and the increased combusted mass from Steps 5 and 6 multiplied by their respective WARM GHG emission and energy use factors

→ **Step 8:** Steps 5 thru 6 were repeated for each individual material.

→ **Step 9:** For a material, its GHG emissions footprint from Step 3 and Step 7 were compared, if Step 3 had a greater negative value then it was labeled with "landfill" signifying landfilling that material generated a smaller GHG emissions footprint than combusting it, but if Step 7 had a greater negative value it was labeled with "combusted".

→ **Step 10:** For a material, Step 9 was repeated but based on its energy use footprint from Step 3 and Step 7.

→ **Step 11:** Steps 9 and 10 were repeated for all materials using the results from Steps 4 and 8.

5.2.2 Application in Minnesota

Table 5-8 showed how we identified if a greater avoidance resulted from landfilling or combusting that material by labeling a material as "landfill" or "combustion". Combusting mixed paper and mixed metals were preferred over landfilling to reduce the GHG emissions footprint. Combusting paper products generates less emissions than landfilling because landfilling these materials generates methane (CH_4) and CO_2, and although WARM does not count the CO_2 because the materials are naturally expectant to release CO_2 when they decompose, the CH_4 is accounted for and has 25 times the global warming potential (GWP) of CO_2 (ICF International, 2016a, 2016d). The combustion and landfilling emission factor for mixed metals were both 0.02 $MTCO_2eq./ton$, so the disposal method with the least mass resulted in the least emissions, and this was combustion (ICF International, 2016d).

From an energy perspective most, materials generated more energy avoidance when combusted than landfilled because those materials have energy content that when combusted offset the use of fossil fuels used to generate electricity (ICF International, 2016b). However, the materials that should be landfilled instead was mixed metals because although they offset energy, the energy content recovered during combustion is not large enough offset the energy of operating and combusting the materials in a waste-to-energy facility.

Table 5-8. Illustration of the Best Disposal Management approach for MN's waste management in 2015, where for each material either landfilling or combusting the material resulted in a smaller footprint. If landfilling the material resulted in more emissions/energy use than combustion then "landfill" is displayed, and if combustion resulted in more emissions/energy use than landfill then "combustion" is displayed.

Material	GHG Emissions Perspective	Energy Use Perspective
Mixed Plastics	Landfill	Combustion
Mixed Paper	Combustion	Combustion
Mixed Metals	Combustion	Landfill
Textiles	Landfill	Combustion
Tires	Landfill	Combustion

5.3 Prioritizing Policy and Technology Approach

5.3.1 Methodology

Across the nation solid waste policy makers are faced with strategically investing in policies and technologies to best manage their waste stream. The prioritizing policy and technology approach compares the environmental impact of various policy and technology scenarios to a current environmental footprint to determine which policy or technology reduces the environmental footprint the most. In this approach we demonstrated how MN policy makers may evaluate various policies or technologies using three hypothetical scenarios as an example. The three scenarios included the following: 1) composting yard trash and food waste, which assumes MN passes a mandatory statute to collect, construct, and operate an organics composting facility; 2) commercial recycling, which assumes MN institutes a statute for mandatory commercial recycling of glass, aluminum cans, steel cans, corrugated paper, plastic bottles, and mixed paper ;and 3) source reducing (or waste prevention of) food waste, where MN implements a policy to encourage restaurants and other consumers to minimize the purchase and then disposal of unconsumed food. The following steps were used to identify which scenario resulted in the most GHG emissions and energy use avoidance using 2015 mass data (Table 3-3):

→ **Step 1:** For the composting yard trash and food waste scenario the mass of yard trash and food waste landfilled were multiplied by 0.15, individually.

> *Note: the 0.15 value represented a 15% reduction of yard trash and food waste landfilled mass. This value was not specific to any policy or regulation.*

→ **Step 2:** The mass corresponding to the 15% landfilled mass from Step 1 was assumed composted and we estimated the scenario's environmental footprint by multiplying the individual masses by the respective WARM GHG emission and energy use factors for composting yard trash and food waste. The composting yard trash and food waste scenario's GHG emissions and energy use footprint will be used in Step 7.

→ **Step 3:** For the commercial recycling scenario the mass of glass, aluminum cans, steel cans, corrugated paper, plastic bottles, and mixed paper landfilled were multiplied by 0.15, individually.

Note: the 0.15 value represented a 15% reduction of glass, aluminum cans, steel cans, corrugated paper, plastic bottles, and mixed paper landfilled mass. This value was not specific to any policy or regulation.

→ **Step 4:** The masses corresponding to the 15% landfilled masses from Step 3 were assumed recycled and we estimated the scenario's environmental footprint by multiplying the individual masses by the respective WARM GHG emission and energy use factors for recycling glass, aluminum cans, steel cans, corrugated paper, plastic bottles, and mixed paper. The composting commercial recycling scenario's GHG emissions and energy use footprint will be used in Step 7.

→ **Step 5:** For the source reducing food waste scenario the mass of food waste landfilled was multiplied by 0.15.

Note: the 0.15 value represented a 15% reduction of food waste landfilled mass. This value was not specific to any policy or regulation.

→ **Step 6:** The mass corresponding to the 15% landfilled mass from Step 5 was assumed source reduced and we estimated its environmental footprint by multiplying the mass by its respective WARM GHG emission and energy use factors for source reducing food waste. The source reducing food waste scenario's GHG emissions and energy use footprint will be used in Step 7.

→ **Step 7:** The GHG emissions and energy use footprints from Steps 2, 4, and 6 were compared; the scenario with the greatest negative values for both footprints should be prioritized.

5.3.2 Application in Minnesota

For each scenario the environmental footprint was estimated and compared to the original 2015 footprint shown and the net difference was plotted in Figure 5-1. Of the three scenarios, the commercial recycling scenario generated the most GHG emissions and energy avoidance, thus this scenario would have the largest impact in decreasing the 2015 environmental footprint. This scenario emphases recycling over composting or combusting. In WARM recycling generates a greater avoidance than combusting or combusting because of the offsets associated with using recycled materials in place of virgin materials. The scenario with the lowest GHG emissions avoidance was the combusting yard trash and tires scenario because combusted yard trash emits nitrous oxide (N_2O), which has a GWP of 298, and combusted tires releases CO_2 (ICF International, 2016d, 2016b). The scenario with the lowest energy use avoidance was the composting yard trash and food waste scenario because of the energy input needed to operate a compositing facility.

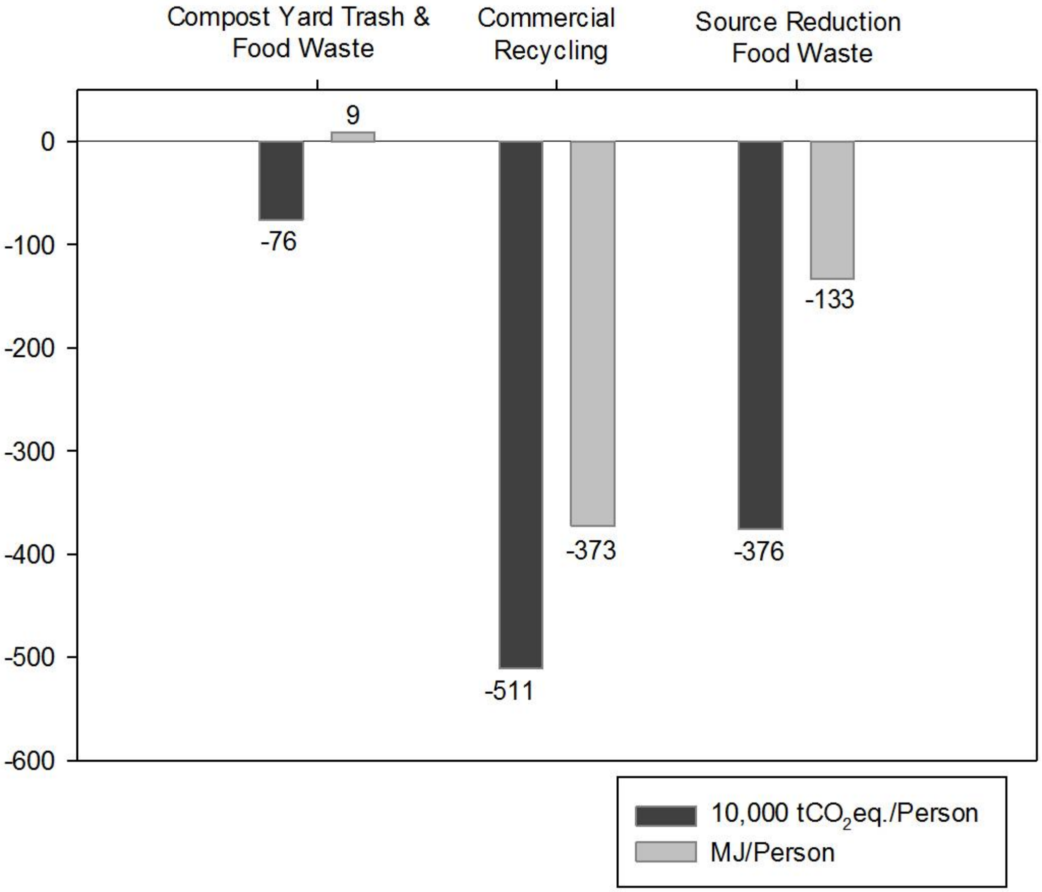


Figure 5-1. Example results of applying the Prioritizing Policy and Technology approach illustrated using three scenarios: 1) composting yard trash and food waste; 2) commercial recycling; and 3) source reduction food waste. Each scenario's environmental footprint was compared to the original 2015 footprint and the net difference is shown.

5.4 Prioritizing Stakeholders Approach

5.4.1 Methodology

The prioritizing stakeholders approach recognizes that certain parties generating MSW have the potential to decrease the environmental footprint. This approach attempts to reduce the environmental footprint by identifying stakeholders associated with the material's GHG emissions/energy use and directing policy makers to institute polices to promote stakeholders reduce their footprints by following SMM. Application of this approach is similar to the prioritizing policy and technology approach, where we illustrate application using examples and compare the environmental impact to determine which stakeholders reduces the environmental footprint the most. The three scenarios evaluated in this approach included: 1) restaurant food waste composting, which assumes restaurant's send their food waste to be composted instead of landfilled; 2) multi-family recycling, which assumes multi-family residents (e.g., apartment complexes) increase their recycling of newspaper, glass, aluminum cans, steel cans, corrugated paper, plastic bottles, and mixed paper; and 3) commercial retailers recycling, which assumes retailers that sell electronics collect and recycle all their electronics. The following steps were used to identify which scenario resulted in the most GHG emissions and energy use avoidance using 2015 mass data (Table 3-3):

→ **Step 1:** For the restaurant food waste composting scenario the mass of food waste landfilled was multiplied by 0.10.

> *Note: the 0.10 value represented a 10% reduction of food waste landfilled mass. This value was not specific to any policy or regulation.*

→ **Step 2:** The mass corresponding to the 10% landfilled mass from Step 1 was assumed composted and we estimated the scenario's environmental footprint by multiplying the mass by the respective WARM GHG emission and energy use factors for composting food waste. The composting food waste scenario's GHG emissions and energy use footprint will be used in Step 7.

→ **Step 3:** For the multifamily recycling scenario the mass of newspaper, glass, aluminum cans, steel cans, corrugated paper, plastic bottles, and mixed paper landfilled were multiplied by 0.10, individually.

> *Note: the 0.10 value represented a 10% reduction of food waste landfilled mass. This value was not specific to any policy or regulation.*

→ **Step 4:** The masses corresponding to the 10% landfilled masses from Step 3 were assumed recycled and we estimated the scenario's environmental footprint by multiplying the individual masses by the respective WARM GHG emission and energy use factors for recycling newspaper, glass, aluminum cans, steel cans, corrugated paper, plastic bottles, and mixed paper. The multifamily recycling scenario's GHG emissions and energy use footprint will be used in Step 7.

→ **Step 5:** For the commercial retailer recycling scenario the mass of electronics landfilled was multiplied by 0.10.

> *Note: the 0.10 value represented a 10% reduction of electronics landfilled mass. This value was not specific to any policy or regulation.*

→ **Step 6:** The mass corresponding to the 10% landfilled mass from Step 5 was assumed source reduced and we estimated its environmental footprint by multiplying the mass by its respective WARM GHG emission and energy use factors for recycling electronics. The commercial retailers recycling scenario's GHG emissions and energy use footprint will be used in Step 7.

→ **Step 7:** The GHG emissions and energy use footprints from Steps 2, 4, and 6 were compared; the scenario with the greatest negative values for both footprints should be prioritized.

5.4.2 Application in Minnesota

For each scenario the environmental footprint was estimated and compared to the original 2015 footprint shown and the net difference was plotted in Figure 5-2. The multi-family recycling scenario generated the largest avoidance because the recycled materials include aluminum cans, which have the largest emission (-9.10 $tCO_2eq.$/person) and energy avoidances (-161,175 MJ/person) compared to the other materials (ICF International, 2016d). The commercial retailers recycling focuses on electronics and although these materials make up a small portion of MN's total generated waste (Table 3-4) their environmental impact is large, especially their energy avoidance when recycled (-30,759 MJ/person) (ICF International, 2016e). MN policy makers can expand the list of scenarios to identify potential stakeholders that when they manage their waste stream using SMM could decrease the overall environmental footprint.

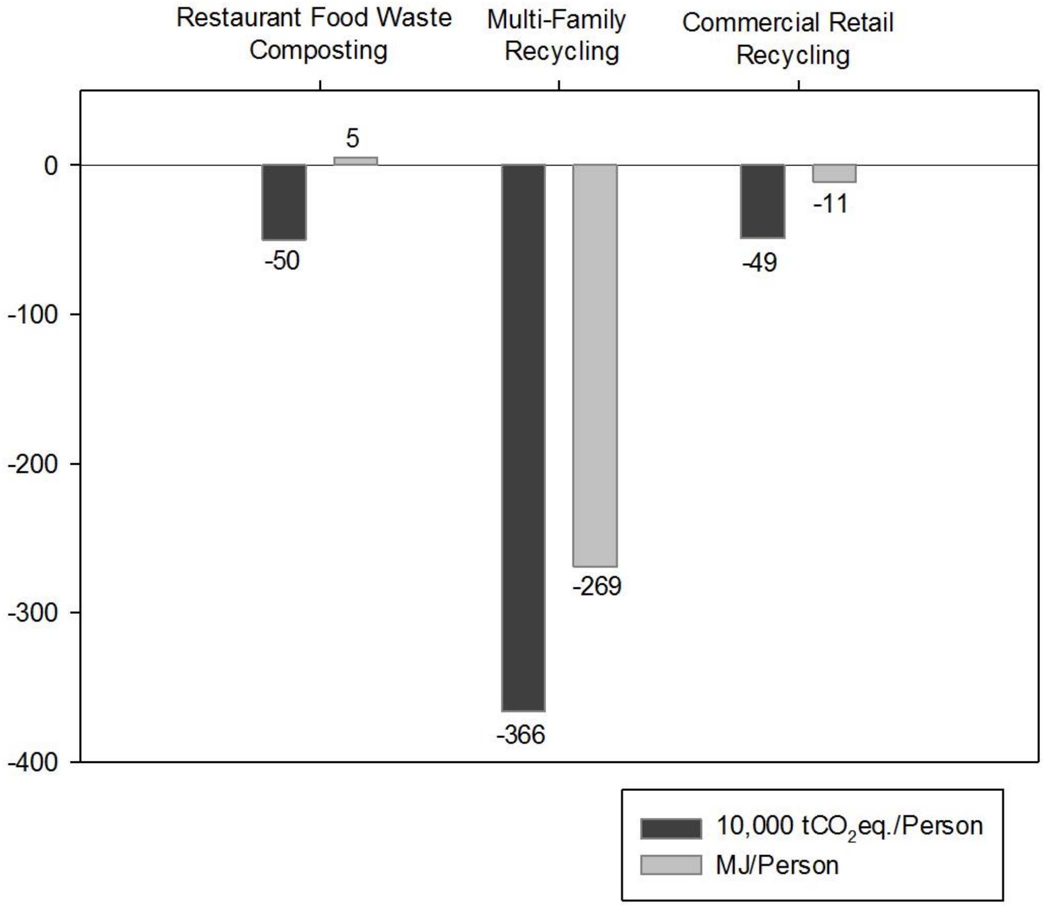


Figure 5-2. Example results of applying the Prioritizing Stakeholders approach illustrated using three scenarios: 1) restaurant food waste composting; 2) multi-family recycling; and 3) commercial retailers recycling. Each scenario's environmental footprint was compared to the original 2015 footprint and the net difference is shown.

5.5 Effective Recycling Rates

5.5.1 Methodology

This approach follows the previous approach applied to Florida and described in Section 2. The data required for this approach was estimated in Table 3-3. We evaluated how MN could apply this approach using two target baselines, a 2005 and a 2015 target baseline and then we compared the estimated 2015 data with the two baselines. We were able to evaluate the use of both a 2005 and 2015 baseline because the data needed was provided directly by MPCA reports or we were able to apply minimal assumptions to

→ **Step C1:** Like Florida's approach, we can use the baseline's recycling rate, GHG emissions and energy footprints to create equivalent LCI-normalized recycling rates. The effective recycling approach calculates the same results as the Florida approach and Eq. 2-5 show the general methodology.

→ **Step C1.1:** We assumed for a baseline (i.e., the hypothetical 2015 target baseline):

$$\mathrm{RR}_{\mathrm{Mass,Baseline}} = \mathrm{LCI}_{\mathrm{Baseline\ Year}} \qquad \text{Eq. 2}$$

Where,

$\mathrm{RR}_{\mathrm{Mass,Baseline}}$ in units of (%) refers to the baseline's mass-based recycling rate.

$\mathrm{LCI}_{\mathrm{\ Baseline}}$ in units of $\left(\frac{\mathrm{tCO_2eq.}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ refers to the baseline's annual GHG emissions and/or energy use footprints.

Note:

a. *For the hypothetical 2005 target baseline,* $RR_{Mass,Baseline}$ *refers to the recycling rate from Step A4 and* $LCI_{\ Baseline}$ *refers to the GHG emissions and energy use footprints from Step A5.*

b. *For the hypothetical 2015 target baseline,* $RR_{Mass,Baseline}$ *refers to the recycling rate from Step B4 and* $LCI_{\ Baseline}$ *refers to the GHG emissions and energy use footprints from Step B5.*

→ **Step C1.2:** Then, we assumed using Eq. 4 that we could create a conversion factor where a 1% mass-based recycling rate was equivalent to a certain GHG emissions or energy use footprint. We calculate this by solving for $\mathrm{LCI}_{\mathrm{\ n}}$:

$$\frac{\mathrm{RR}_{\mathrm{Mass,Baseline}}}{\mathrm{LCI}_{\mathrm{\ Baseline}}} = \frac{1\%}{\mathrm{LCI}_{\mathrm{\ n}}} \qquad \text{Eq. 3}$$

$$1\% = \mathrm{LCI}_{\mathrm{\ n}} \qquad \text{Eq. 4}$$

Where,

$\mathrm{LCI}_{\mathrm{\ n}}$ is in units of $\left(\frac{\mathrm{tCO_2eq.}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ and is equivalent to the $\left(\frac{\mathrm{tCO_2eq.}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ associated with a 1% mass-based recycling rate.

D. To calculate the initial 2015 solid waste management progress toward the 2005 and 2015 target baseline's alternative metrics:

→ **Step D1:** Apply the 2005 and 2015 baseline's conversion factors to the year-of-interest's footprint to calculate it's LCI-normalized recycling rate(s) (referred to as $\mathrm{R}_{\mathrm{LCI,Year\ of\ Interest}}$):

$$\mathrm{R}_{\mathrm{LCI,Year\ of\ Interest}} = \mathrm{LCI}_{\mathrm{\ Year\ of\ Interest}} \left(\frac{1\%}{\mathrm{LCI}_{\mathrm{\ n}}}\right) \qquad \text{Eq. 5}$$

Where,

$\mathrm{RR}_{\mathrm{LCI,Year\ of\ Interest}}$, in units of (%) refers to the year-of-interest's LCI-normalized recycling rate.

$\mathrm{LCI}_{\mathrm{Year\ of\ Interest}}$ units of $\left(\frac{\mathrm{tCO_2eq.}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ refers to the year-of-interest annual GHG emissions and/or energy use footprints.

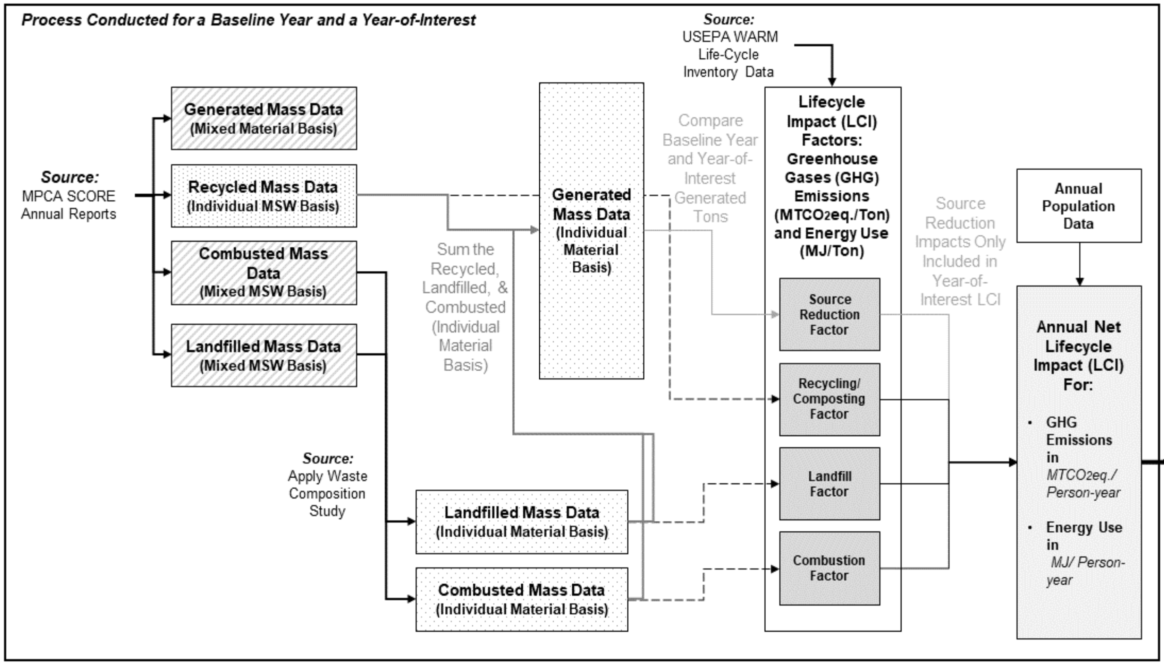
> *Note: If the year-of-interest and the baseline year were not both the same (e.g., baseline is 2005 and year-of-interest is 2015) then the $RR_{LCI,Year\ of\ Interest}$ should include the impacts of waste generated per person more of in 2015 than in 2005 (source generated waste) and waste generated per person less of in 2015 than in 2005 (source reduced waste). We would do this for each material by subtracting their 2015 generation rate from their 2005 rate. Then to calculate the environmental impact we would multiply that difference in mass by the material's WARM source reduction GHG emissions and energy factors and by -1.*

5.5.2 Application in Minnesota

For the hypothetical 2005 and 2015 target baseline its associated recycling rate and environmental footprints are presented in Table 5-9. We used this information and the Equations 4-7 to estimate conversion factors shown in Table 5-10. Figure 5-4 presents how the hypothetical 2005 target baseline compared to the estimated 2015 data. Figure 5-5 presents how the hypothetical 2015 target baseline compared to the estimated 2015 data. The bar labeled mass refers to the 2015 mass-based recycling rate, GHG refers to the 2015 GHG-normalized recycling rate, energy use refers to the 2015 energy-normalized recycling rate. The solid line represents the baseline's mass-based recycling rate, GHG emissions footprint, and the energy footprint.

In MN the LCI-normalized recycling rate were greater than the mass-based recycling rate, suggesting that MN decision makers focused efforts on materials with a larger environmental impact than a mass impact. The difference between the mass-based recycling rate and the LCI-normalized recycling rates is that the mass-based rate only accounts for the weight of a material, while the LCI-normalized rate accounts for the weight of a material and its individual environmental impact. Also, the mass-based rate only incorporates the mass impact of each material from the year-of-interest and not the baseline year. The LCI-normalized rate incorporates the mass and environmental impacts associated with each material from the year-of-interest and the baseline year.

Figure 5-4 presents how the 2015 recycling rate and environment footprints compared to the 2005 hypothetical baseline. In MN the LCI-normalized recycling rate (including source reduction credit) were greater than the mass-based recycling rate. The avoidance associated with waste prevented was greater than the GHG emissions/energy use associated with waste generated resulting in a net avoidance. However, there may be net GHG emissions/energy use cases that instead of contributing progress they take away progress toward the target. In these cases, the LCI-normalized recycling rate would be greater without waste prevention credit than with the credit, and when including waste prevention credit, the LCI-normalized recycling rate becomes smaller. For example, if this was the case in MN the bars labeled source reduction credit in Figure 5-4 would disappear and the grey bars become shorter.



Alternative Metrics:
LCI-Normalized Recycling Rates Equivalent to Recycling Rate Target

Assume for a baseline:

$$\mathrm{RR}_{\mathrm{Mass,Baseline}} = \mathrm{LCI}_{\mathrm{Baseline\ Year}} \qquad \text{Eq. 1}$$

Then, solve for LCI_n:

$$\frac{\mathrm{RR}_{\mathrm{Mass,Baseline}}}{\mathrm{LCI}_{\mathrm{Baseline}}} = \frac{1\%}{\mathrm{LCI}_{\mathrm{n}}} \qquad \text{Eq. 2}$$

$$\mathrm{LCI}_{\mathrm{n}} = 1\% \qquad \text{Eq. 3}$$

Apply the conversion factor to a year-of-interest:

$$\mathrm{R}_{\mathrm{LCI,Year\ of\ Interest}} = \mathrm{LCI}_{\mathrm{Year\ of\ Interest}} \left(\frac{1\%}{\mathrm{LCI}_{\mathrm{n}}}\right) \qquad \text{Eq. 4}$$

Where,

$\mathrm{RR}_{\mathrm{Mass,Baseline}}$ in units of (%) refers to the baseline's mass-based recycling rate.

$\mathrm{LCI}_{\mathrm{Baseline}}$ in units of $\left(\frac{\mathrm{MTCO_2\,eq}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ refers to the baseline's annual GHG emissions and/or energy use footprints.

$\mathrm{LCI}_{\mathrm{n}}$ is in units of $\left(\frac{\mathrm{MTCO_2\,eq}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$.

$\mathrm{RR}_{\mathrm{LCI,Year\ of\ Interest}}$, in units of (%) refers to the year-of-interest's LCI-normalized recycling rate.

$\mathrm{LCI}_{\mathrm{Year\ of\ Interest}}$ units of $\left(\frac{\mathrm{MTCO_2\,eq}}{\mathrm{Person}}\right)$ and/or $\left(\frac{\mathrm{MJ}}{\mathrm{Person}}\right)$ refers to the year of interest annual GHG emissions and/or energy use footprints.

Figure 5-3. MN-specific methodology to estimate mass data (recycled, landfilled, combusted, landfilled & recycled ash) used as inputs to calculate a baseline year and year of interest's net lifecycle (LCI) impact (in GHG emissions and energy use) which is then converted to an LCI-normalized recycling rate equivalent to a recycling rate target.

Table 5-9. Recycling rate and environmental footprint for the 2005 and 2015 hypothetical baseline

State	Recycling Rate	GHG Emissions (tCO2eq./Person)	Energy Use (MJ/Person)
2005 Baseline	52.2%	-1.160	-12,202
2015 Baseline	52.5%	-0.964	-10,924

Table 5-10. Conversion factors for MN used in the Effective Recycling Rates approach. The 1% recycling rate refers to the recycling rate and the environmental footprints are associated with the 2005 and 2015 targets, shown in Table 5-9 and calculated using Equations 4-7.

Region	Recycling Rate		GHG Emissions (tCO2eq./ Person/ 1% Recycling Rate)	Energy Use (MJ/ Person/ 1% Recycling Rate)
2005 Baseline	1%	=	-0.022	-233.9
2015 Baseline	1%	=	-0.019	-212.0

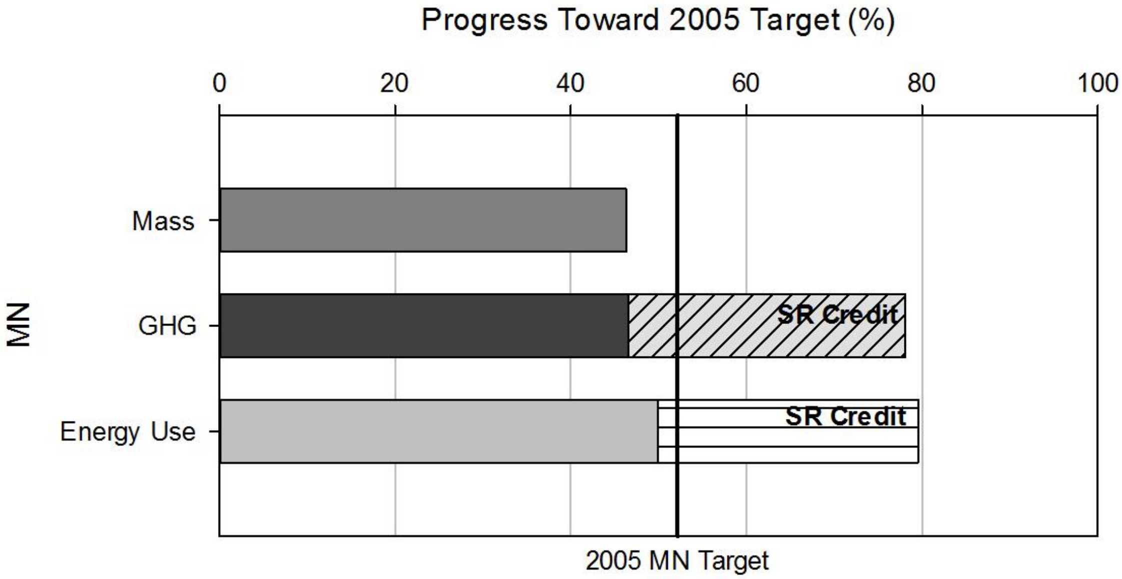


Figure 5-4. The Effective Recycling Rates approach applied to MN using a 2005 hypothetical baseline. A 2005 baseline was created and the 2015 recycling rate, and environmental footprints were compared to see the progress of the 2015 performance to the 2005 performance. The bar labeled mass refers to the 2015 mass-based recycling rate, GHG refers to the 2015 GHG-normalized recycling rate, energy use refers to the 2015 energy-normalized recycling rate. The solid line represents the baseline's mass-based recycling rate, GHG emissions footprint, and the energy footprint. SR Credit refers to source reduced (or generated) waste's contribution to the LCI-normalized recycling rates.

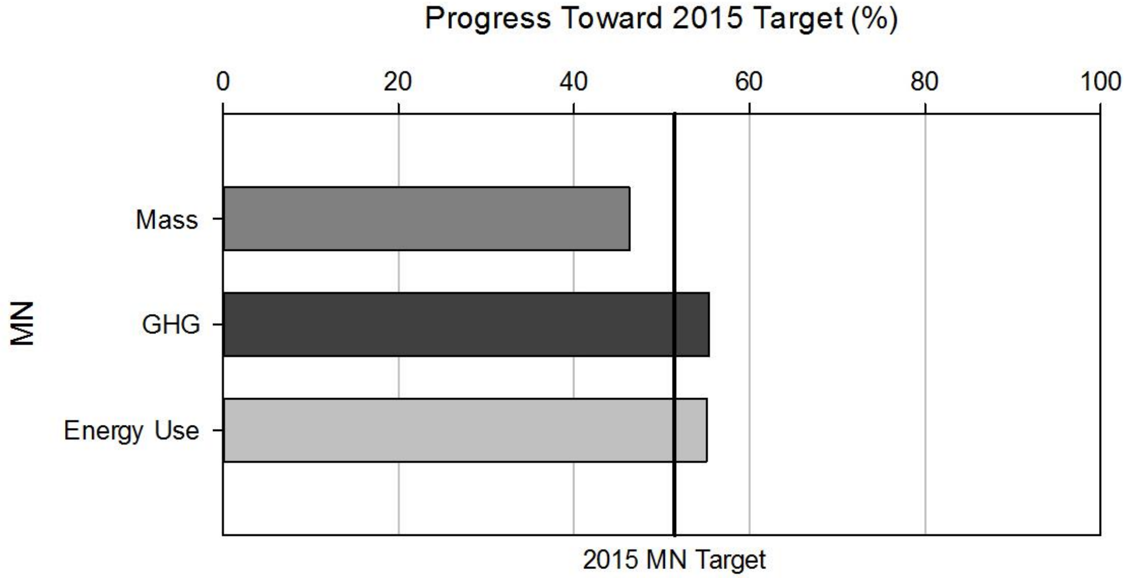


Figure 5-5. The Effective Recycling Rates approach applied to MN using a 2005 hypothetical baseline. A 2015 hypothetical baseline was created and the 2015 recycling rate, and environmental footprints were compared to see the progress of the 2015 performance to the 2015 target. The bar labeled mass refers to the 2015 mass-based recycling rate, GHG refers to the 2015 GHG-normalized recycling rate, energy use refers to the 2015 energy-normalized recycling rate. The solid line represents the baseline's mass-based recycling rate, GHG emissions footprint, and the energy footprint.

CONCLUSION AND RECOMMENDATIONS

This report provided details on the methodologies taken to collect mass data for MN for 2005 and 2015, to evaluate remaining areas where mass data is lacking and needed for SMM-based approaches, and to demonstrate application of the SMM-based approaches in MN.

We followed various assumptions and calculations to estimate the required individual materials generated, recycled, combusted, and landfilled masses needed to evaluate as inputs for calculating the GHG emissions and energy use footprints used in the SMM-based approaches. Although we were able to estimate the above listed mass dispositions for individual materials in both 2005 and 2015, MN should still focus their efforts on better tracking and reporting systems so that the environmental footprints are calculated using actual reported numbers instead of estimated values. We calculated MN's recycling rate as 41.4% and 43.7% in 2005 and 2015, respectively. These values do not include recycled miscellaneous or C&D debris. From the mass-based recycling rate, we see that MN has made progress in recycling more of their waste stream since 2005, but we cannot identify from the recycling rate whether MN prioritized materials with a large potential to decrease their environmental footprint.

The SMM model can be applied in various ways and we focused on five different application approaches and demonstrated their application in MN using 2015 data. The approaches were categorized by how the SMM model can be used; the two methods the SMM model can be used were to prioritize and strategically plan and to measure performance outcomes. We formulated and demonstrated four approaches that used the SMM model to prioritize and strategically plan, that included: 1) Best Target Materials Recycling, 2) Best Disposal Management, 3) Prioritizing Policy and Technology Approach, and 4) Prioritizing Stakeholders. Of these four approaches MN policy makers can use existing infrastructure and use the SMM model to follow the Best Target Materials Recycling and Best Disposal Management approaches. From these two approaches, policy makers can use the SMM model to prioritize the recycling of paper and metal products to minimize their GHG emissions and energy use footprints. They can also strategically plan to combust most mixed plastics, paper, and metals to minimize their environmental footprints. The Prioritizing Policy and Technology and Prioritizing Stakeholders approaches use the SMM model to identify from a set of potential management scenarios the best scenario based on its potential impact to reduce MN's environmental footprint. MN policy makers can follow the methodology presented here to further evaluate other potential scenarios while using the SMM model's principles.

The last approach called the Effective Recycling Rates approach uses the SMM model to measure their system's environmental progress. Policy makers can measure their recycling progress using the SMM-based metric, which when compared to the traditional mass-based recycling rate was greater and it achieved the hypothetical SMM target's mass-based and SMM-based values. This approach showed that MN policy makers can incorporate the SMM model's principles into metrics that can reach policy targets (e.g., recycling rate goals) while quantifying the environmental impacts.

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R.W. Beck, 2000. Minnesota Statewide MSW Composition Study.

APPENDIX

Table A1. Waste composition data extracted from the 2000 Minnesota Waste Composition Study (R.W. Beck, 2000).

Item No.	Material	Total Percentage of Waste Stream	Item No.	Material	Total Percentage of Waste Stream
1	**Paper**	**34.3%**	34	**Organics**	**25.7%**
2	Newspaper (ONP)	4.1%	35	Yard Waste- grass and leaves	2.1%
3	High Grade Office	3.1%	36	Yard Waste- woody material	0.2%
4	Magazines/ Catalogs	2.5%	37	Food waste	12.4%
5	Uncoated OCC- recyclable	6.2%	38	wood pallets	2.6%
6	Uncoated OCC- nonrecyclable	0.5%	39	treated wood	3.0%
7	Coated OCC	0.2%	40	Untreated wood	1.9%
8	Boxboard	2.5%	41	Diapers	2.1%
9	Mixed paper- recyclable	6.0%	42	Other organic material	1.4%
10	Mixed paper- nonrecyclable	9.2%	43	**Problem Materials**	**1.9%**
11	**Plastic**	**11.4%**	44	Televisions	0.0%
12	PET Bottles/Jars - clear	0.4%	45	Computer Monitors	0.0%
13	PET Bottles/Jars - colored	0.2%	46	Computer Equipment/ Peripherals	0.2%
14	Other PET	0.1%	47	Electric and Electronic Products	1.6%
15	HDPE Bottles - natural	0.3%	48	Batteries	0.1%
16	HDPE Bottles - colored	0.2%	49	Other	0.0%
17	PVC	0.1%	50	**HHW/HW**	**0.6%**
18	Polystyrene	0.8%	51	Latex Paint	0.01%
19	Film- transport packaging	0.3%	52	Oil paint	0.01%
20	Other Film	3.5%	53	unused Pesti./Fungi/Herbi-cides	0.02%
21	Other Containers	0.6%	54	unused cleaners and solvents	0.02%
22	Other non-containers	4.9%	55	compressed fuel containers	0.02%
23	**Metal**	**5.1%**	56	automotive - antifreeze	0.02%
24	Aluminum Bev. Containers	0.7%	57	automotive - used oil filters	0.1%
25	Other Aluminum	0.5%	58	other	0.4%
26	Ferrous Containers	0.9%	59	**Other Waste**	**18.3%**
27	Other Ferrous	2.9%	60	Textiles	2.7%
28	Other Non-ferrous	0.1%	61	Carpet	2.4%
29	**Glass**	**2.8%**	62	Sharps and Infectious Waste	0.0%
30	Clear Containers	1.3%	63	Rubber	0.8%
31	Green Containers	0.4%	64	C&D Debris	2.8%
32	Brown Containers	0.4%	65	Household Bulky Items	3.4%
33	Other Glass	0.7%	66	Empty HHW/HW Containers	0.4%
			67	Miscellaneous	5.8%

Table A2. Waste composition data extracted from the 2013 Minnesota Waste Composition Study (Burns & McDonnell, 2013).

Item No.	Material	Total Percentage of Waste Stream	Item No.	Material	Total Percentage of Waste Stream
1	**Paper**	**24.5%**	34	**Organics**	**31.0%**
2	Newspaper (ONP)	1.4%	35	Yard Waste	2.8%
3	High Grade Office	1.1%	36	Food Waste	17.8%
4	Magazines/ Catalogs	0.8%	37	Wood	5.7%
5	Phone Books	0.1%	38	Other organic material	4.7%
6	Gable Top/Aspetic Containers/Cartons	0.3%	39	**Electronics**	**1.2%**
7	OCC and Kraft Bags	3.7%	40	Laptops	0.0%
8	Boxboard	1.6%	41	Computer Models	0%
9	Compostable Paper	9.8%	42	Televisions	0.0%
10	Mixed Recyclable Paper	3.4%	43	Printers	0.1%
11	Non-Recyclable Paper	2.3%	44	All other electronic items	1.1%
12	**Plastic**	**17.9%**	45	**HHW**	**0.4%**
13	#1 PET Beverage Containers	0.8%	46	Batteries	0.0%
14	Other PET (e.g., Jars and Clamshells)	0.5%	47	Mercury Containing Lamps	0%
15	HDPE Bottles/Jars	0.5%	48	Paint Containers	0.2%
16	Other HDPE	0.6%	49	Oil Containers & Filters	0%
17	PVC - #3	0.01%	50	Smoke Detectors	0%
18	Polystyrene - #6	1.0%	51	Other HHW	0.2%
19	LDPE (Rigids) - #4	0.1%	52	**Other Waste**	**18.3%**
20	Polypropylene	0.6%	53	Mattresses/ Box Springs	0.4%
21	Other #7 Plastics	0.1%	54	Appliances & Furniture	3.0%
22	PLA & Compostable Plastics	0.01%	55	Textiles & Leather	4.7%
23	Bag and Film Plastic	6.6%	56	Carpet	2.3%
24	Other Plastic (nonpackaging)	7.1%	57	Sharps and Infectious Waste	0.01%
25	**Metal**	**4.5%**	58	Other Not Elsewhere Classified	8%
26	Aluminum Bev. Containers	0.4%			
27	Other Aluminum	0.7%			
28	Steel/Tin (Ferrous) Containers	0.7%			
29	Other Metal	2.7%			
30	**Glass**	**2.2%**			
31	Beverage Container Glass	1.3%			
32	Glass Containers	0.5%			
33	Other (Non-Container) Glass	0.4%			

Table A3. Recycling composition and mass associated extracted from the 2005 and 2015 Report on SCORE Programs (Minnesota Pollution Control Agency, 2005 & 2015).

Item No.	Baseline Year (2005)		Year-Of-Interest (2015)	
	Material	Recycled Mass (Tons)	Material	Recycled Mass (Tons)
1	**Paper**	**923,837**	**Paper**	**863,594**
2	Corrugated	365,245	Cardboard	410,124
3	Magazine/Catalog	34,698	Magazine/Catalog	18,773
4	Mixed Paper	219,576	Mixed Paper	231,996
5	Newsprint	197,712	Newsprint	134,043
6	Office Paper	41,027	Office Paper	30,799
7	Other Paper	62,177	Other Paper	37,446
8	Phone Book	1,730	Phone Book	412
9	Computer Paper	1,671		
10	**Metal**	**490,100**	**Metal**	**503,363**
11	Aluminum	27,386	Aluminum	24,731
12	Co-Mingled Alum/Steel/Tin	52,890	Ferrous Metals	398,514
13	Other Ferrous & Non-Ferrous	388,562	Non-Ferrous Metals	80,118
14	Steel/Tin Cans	21,262		
15	**Glass**	**119,464**	**Glass**	**129,298**
16	Food & Beverage	81,427	Food & Beverage	101,953
17	Other Glass	38,037	Other Glass	27,344
18	**Plastics**	**47,774**	**Plastics**	**62,871**
19	Film Plastic	5,375	Film Plastic	9,248
20	HDPE	2,728	HDPE	6,986
21	Mixed Plastic	33,667	Mixed Plastic	34,560
22	Other Plastics	2,618	Other Plastics	3,543
23	PET	3,279	PET	7,976
24	Polystyrene	107	Polystyrene	558
25	**Organics**	**796,873**	**Organics**	**575,218**
26	Food Waste	171,146	Food to Livestock	255,197
27	Carpet	167	Food to People	12,179
28	Textiles	15,446	Source Separated Composting	65,426
29	Pallets	98,618	Yard Waste Composting	202,352
30	Unspecified or Other	511,496	Other Organics	40,065
31	**Problem Materials**	**113,750**	**Problem Materials**	**118,315**
32	Antifreeze	698	Antifreeze	614
33	Electronics	7,028	Electronics	18,915
34	Fluorescent & Hid Lamps	632	Fluorescent & Hid Lamps	649
35	Latex Paint	2,063	Latex Paint	2,345
36	Major Appliances	39,361	Major Appliances	25,202
37	Used Oil	7,391	Oil Filters	3,301
38	Used Oil Filters	3,048	Used Oil	12,377
39	Vehicle Batteries	35,087	Vehicle Batteries	21,796
40	Waste Tires	17,169	Waste Tires	33,116
41	HHW	1,274		
42			**Other Materials**	**145,255**
43			Carpet	408
44			Pallets	73,528
45			Textiles	12,267
46			Other	58,215
47			Mattresses and Box Springs	837
	Total	**2,491,798**	**Total**	**2,397,914**

Table A4. Re-organized landfilled/combusted materials for 2005 and 2015. The materials column shows the re-organized materials category and the assumptions columns (which references materials from Table A1 for 2005 and Table A2 for 2015) shows which materials are included in the re-organized material categories.

Material	Assumptions for 2005 Disposed Materials	Assumptions for 2015 Disposed Materials
Newspaper	2	2
Glass	29	30
Aluminum Cans	24	26
Steel Cans	26	28
Corrugated Paper	5 thru 8	7 + 8
Plastic Bottles	12 thru 16	13 thru 16
Yard Trash	35 + 36 + 38 thru 40	35 + 37
Mixed Plastics	17 thru 22	17 thru 24
Food Waste	37	36
Mixed Paper	3 + 4 +9 +10	3 thru 6+ 9 thru 11
Mixed Metals	25 + 27 + 28	27 + 29
Textiles	60 + 61	55 + 56
Tires	63	Not Estimated
Electronics	43	39 + 54 + 46
C&D Debris	64	Not Estimated
Miscellaneous	41 + 42 + 50 + 62 +65 thru 67	38 + 45 + 53 + 57 + 58

Table A5. Re-organized recycled materials for 2005 and 2015. The materials column shows the re-organized materials category and the assumptions columns (which references materials from Table A3) shows which materials are included in the re-organized material categories.

Material	Assumptions for 2005 Recycled Materials	Assumptions for 2015 Recycled Materials
Newspaper	5	5
Glass	15	15
Aluminum Cans	11	11
Steel Cans	14	12
Corrugated Paper	2	2
Plastic Bottles	20 + 23	20 + 23
Yard Trash	29	29 + 44
Mixed Plastics	19 + 21 + 22 +24	19 + 21 + 22 +24
Food Waste	26	26 + 27 + 28
Mixed Paper	3 thru 9	3 thru 8
Mixed Metals	12 + 13	12 + 13
Textiles	27 + 28	43 + 45
Tires	40	40
Electronics	33 + 36 + 39	33 + 36 + 39
C&D Debris	Not Estimated	Not Estimated
Miscellaneous	30 + 32 + 34 + 35 +37 + 38 +41	30 + 32 + 34 + 35 +37 + 38 +41 + 46 + 47