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Analysis of material recovery facilities for use in life-cycle assessment

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ABSTRACT

Insights derived from life-cycle assessment of solid waste management strategies depend critically on assumptions, data, and modeling at the unit process level. Based on new primary data, a process model was developed to estimate the cost and energy use associated with material recovery facilities (MRFs), which are responsible for sorting recyclables into saleable streams and as such represent a key piece of recycling infrastructure. The model includes four modules, each with a different process flow, for separation of single-stream, dual-stream, pre-sorted recyclables, and mixed-waste. Each MRF type has a distinct combination of equipment and default input waste composition. Model results for total amortized costs from each MRF type ranged from $19.8 to $24.9 per Mg (1 Mg = 1 metric ton) of waste input. Electricity use ranged from 4.7 to 7.8 kW h per Mg of waste input. In a single-stream MRF, equipment required for glass separation consumes 28% of total facility electricity consumption, while all other pieces of material recovery equipment consume less than 10% of total electricity. The dual-stream and mixed-waste MRFs have similar electricity consumption to a single-stream MRF. Glass separation contributes a much larger fraction of electricity consumption in a pre-sorted MRF, due to lower overall facility electricity consumption. Parametric analysis revealed that reducing separation efficiency for each piece of equipment by 25% altered total facility electricity consumption by less than 4% in each case. When model results were compared with actual data for an existing single-stream MRF, the model estimated the facility's electricity consumption within 2%. The results from this study can be integrated into LCAs of solid waste management with system boundaries that extend from the curb through final disposal.

1. Introduction

Life-cycle assessment (LCA) of solid waste management (SWM) alternatives requires a modeling framework that links detailed process-level operations within a broader system that can quantify impacts from waste generation through final disposal and resource recovery. The model described here has been used to develop material recovery facility (MRF) cost and energy consumption estimates for use in the Solid Waste Optimization Life-cycle Framework (SWOLF), which can be used to conduct LCA that optimizes the flow of different waste fractions within a prescribed system boundary across a set of user-defined time stages (Levis et al., 2013). However, the utility of such a framework depends critically on the quality and representativeness of process-level data used to characterize the unit processes within the system boundary. For complex unit processes such as landfills, anaerobic digesters, or MRFs, a single set of fixed industry-average data estimates cannot accurately predict the performance of individual facilities that include numerous design and operational choices and vary with waste composition. Improved estimates require unit process models that can relate different facility configurations and input waste compositions to changes in the resultant cost, energy consumption, and product flows, and such process models should be designed in a flexible manner to enable scenario exploration within a given LCA (Laurent et al., 2014). While existing inventory databases such as EcoInvent (2010) can provide aggregated inventory estimates for such processes, more representative assessments require specific knowledge of constituent sub-processes informed by state-of-the-art industry data.

The purpose of this paper is to present a detailed and novel process model that characterizes state-of-the-art MRFs, which can be used for life-cycle modeling of SWM systems. MRFs are an integral part of the SWM system because they often determine the amount of collected recyclable material that can be recovered for recycling. Though their integration into the SWM system means that MRFs cannot be analyzed independently of the other SWM system components, detailed standalone MRF process models, like the one presented here, are essential to accurately model the life-cycle impacts of full SWM systems. Recyclable materials present in

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municipal solid waste (MSW) have increasingly gained the attention of SWM decision makers, as recycling of MSW can contribute to sustainability-related objectives including resource recovery, reduced energy consumption, and lower emissions. For example, the European waste framework directive created a 2020 recycling target of 50% of MSW by mass for a number of fractions (EU, 2008). In the U.S., many states and cities have instituted landfill diversion goals. California and Florida have both set a 75% diversion target for 2020 (California, 2012; FDEP, 2010), while cities such as San Francisco, Oakland, and Seattle have set "zero waste" goals with the intent of eliminating landfill disposal (San Francisco Environment, 2013; Oakland, 2013; Seattle, 2013). In addition to increased waste diversion, the environmental benefits of recycling include the avoided use of virgin resources and energy savings (Merrild et al., 2012).

Only limited work has been done to systematically characterize MRF operations and the resulting emissions. Fitzgerald et al. (2012) quantified greenhouse gas emissions at 3 MRFs to compare the impact of dual versus single-stream facilities. However, the study did not consider system costs and it was not clear whether the purity of recovered materials was considered, as the presence of residual materials was higher than expected. Franchetti (2009) modeled MRF economics, but did not consider energy requirements or environmental emissions. Chester et al. (2008) examined the total system energy requirement and greenhouse gas emissions from implementing recycling strategies but did not model MRFs in detail. Themelis and Todd (2004) investigated recycling systems used in New York City, but did not quantify environmental impacts. With respect to MRF process models, Nishtala (1995) developed a model that quantified MRF costs and emissions, but it is now outdated because modern MRFs include several pieces of automated separation equipment that were not in use 20 years ago. Velis et al. (2013) used material flow analysis to analyze a solid recovered fuel process that is similar to the mixed-waste MRF modeled here. However, the input waste stream is bio-dried and shredded, so the results are not directly comparable. None of the aforementioned models allocate energy use and costs using a mass balance approach. The configuration and layout of MRF-related separation equipment depends critically on the input stream to the facility. MRFs can be designed to accept all recyclables in a single-stream, recyclables mixed with non-recyclables (mixed waste), recyclables separated into a fiber and non-fiber stream (dual stream), or pre-sorted recyclables. As a result, the waste stream type accepted by the MRF determines the required separation equipment, which in turn determines recovery efficiencies and energy requirements to run the equipment within the facility, which can then be used to build a MRF life-cycle inventory.

This study builds on previous work by developing a comprehensive, bottom-up model of MRFs that process (1) a single comingled recyclables stream, (2) mixed waste, (3) dual-stream and (4) pre-sorted recyclables. The resultant model is used to estimate MRF energy consumption and total cost. While the development of the MRF process model described here does not itself constitute an LCA, it is designed to be used within an LCA framework, and therefore needs to be informed by LCA considerations such as function, functional unit, system boundary, and allocation. Cost and energy are tracked both because environmental performance and cost are of interest to the recycling community, and they are required by SWOLF, which can use the total system-wide cost of SWM as an objective function or constraint. More broadly, we believe that LCA should include life-cycle costing if it is to be used to inform real world decisions that are largely driven by economics. This paper is organized as follows. Section 2 describes the modeling approach, including a discussion of the assumed system boundary and functional unit, and the data developed for this process model, which has been obtained largely through discussions with MRF operators and equipment vendors. Section 3 presents results from the different MRF types and draws insights from the analysis.

2. Materials and methods

A spreadsheet-based LCA process model was developed to represent each of the four types of MRFs described above. Major inputs to the model include cost and energy consumption estimates for each piece of MRF equipment and the separation efficiencies for every modeled waste component associated with each piece of separation equipment, which are similar to the transfer coefficients used in Rotter et al. (2004) and Velis et al. (2010). MRF performance is directly related to the composition of the incoming waste stream, so a MRF process model should be capable of assessing performance associated with processing each waste component and accounting for changes to the incoming waste stream composition (e.g., waste with a higher ferrous fraction requires a larger magnet).

2.1. System boundaries and functional units

The system boundary for each MRF process model begins at the tipping floor after waste is emptied from the collection vehicle. The boundary includes the production and combustion of all fuel used onsite, the production of all consumed electricity, and baling wire, which is a significant cost for MRFs (Combs, 2012). The system boundaries do not extend to the conversion of the recovered materials into new products or the offset from avoided virgin material production. The system boundaries are narrowly drawn around the MRFs to develop a detailed characterization of MRF life-cycle performance, which can be incorporated into solid waste LCAs with broader system boundaries (e.g., the entire solid waste system).

The function of all MRFs is to separate a waste stream into streams of saleable recyclables and a residual stream for final disposal that contains non-recyclable materials and non-recovered recyclables. The functional unit for each MRF type is 1 Mg (1 Mg = 1 metric ton) of waste as-delivered to the MRF. Because the composition and number of streams delivered to each MRF type varies, the functional unit must be defined for each MRF type. Because the functional unit differs across MRF types, direct comparisons of energy consumption are not meaningful. The composition of waste arriving at each MRF type is shown in Table 1. The mixed-waste stream composition represents a complete residential waste stream. While the single-stream, dual-stream, and pre-sorted MRF compositions are identical, the number of streams delivered to each MRF type differs. Across these three MRF types, we assume that recycling program participation rates and source separation rates remain constant while only the number of waste streams changes. The assumed composition of the waste stream as-delivered to the MRF is based on the residential recycling composition of Seattle (Cascadia, 2011). The Seattle composition was selected because it includes glass recycling, unlike ODEQ (2011), and contaminants, unlike Beck (2005). The U.S. EPA Waste Characterization Report (2010), which reports a recyclable stream composition that includes all recovered materials, indicates that OCC (old corrugated containers) represents 40% of the recovered stream. Since most OCC is baled at commercial locations and is not mixed with the residential waste stream, this composition likely overestimates the significance of OCC at a MRF receiving residential recyclables. However, to capture the sensitivity of results to waste composition variation, the single-stream MRF model was run with the ODEQ (2011), Beck (2005), and U.S. EPA (2010) compositions to explore the sensitivity of the results to the inlet