Environmental Impacts of Recycling Compared to Other Waste Disposal Methods

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Executive Summary

Non-regulated mixed plastic waste represents a large portion of the solid waste generated by healthcare facilities. Healthcare waste management decision makers and influencers must choose from a number of disposal options to deal with this growing environmental burden. HPRC undertook this life cycle assessment (LCA) literature survey to provide the industry additional background on the environmental impacts of the various plastics disposal methods so they can make a more informed choice.

The studies conclude that in most cases mechanical recycling of waste plastics has less environmental impact than alternative disposal methods. Tables are provided to help readers apply the results to their own disposal requirements. Options reviewed included mechanical recycling, feedstock recycling, incineration with energy recovery, and engineered landfills. The literature survey also highlights the need for additional LCAs studies that are specific to the unique needs and constraints within the healthcare industry for various regions.

The selected LCAs address mixed plastics found in municipal waste and are not specific to healthcare. Household waste studies are included because there are limited industrial waste LCA studies. Plastic wastes from households include many of the same plastics used by healthcare facilities.

The LCAs make certain assumptions that will not apply to all geographies and waste streams. The quality of the waste stream may limit the disposal options and their costs. The possibility for recycled plastics to be used in new products will depend on the application. In general, mechanically recycled plastics cannot meet the traceability and other requirements for medical products so are unlikely to be used in their manufacture. The technologies available and the geographic region of disposal affect environmental impacts, such as the efficiency of energy recovery from incineration or the transport distance to a recycling facility.

LCA results depend on the scope and gating of materials. Comparisons within an LCA study of various materials and recycling options take this into account. Comparisons between different LCA studies may be helpful as general guidance only. The types of environmental impacts assessed varied across the reviewed studies, making it difficult to compare the results for different disposal scenarios and waste streams. The scope did not include biohazardous waste or other regulated wastestreams. This literature survey also did not include the economics of disposal methods, though disposal cost data are reported when available. These costs address disposal only, not a total cost of ownership of a product life cycle.

Introduction

Recycling waste materials so that they may be used again in new products is generally promoted as a key strategy to protect the environment and conserve natural resources. The familiar "3Rs" encourage us to reduce, reuse, and recycle, in that order of preference. An extension of this waste hierarchy concept, which is used in different versions to inform waste management policy worldwide, ranks recycling above energy recovery (waste-to-energy) or recovery of materials or fuels from waste and disposal to landfill as the least preferred option (see Figure 1). Recycling is endorsed as environmentally beneficial because it reduces the amount of materials that would otherwise go to landfill or incineration and reduces the amount of new raw materials that needs to be collected and processed for use in new products, resulting, for example, in energy savings and less greenhouse gas emissions.

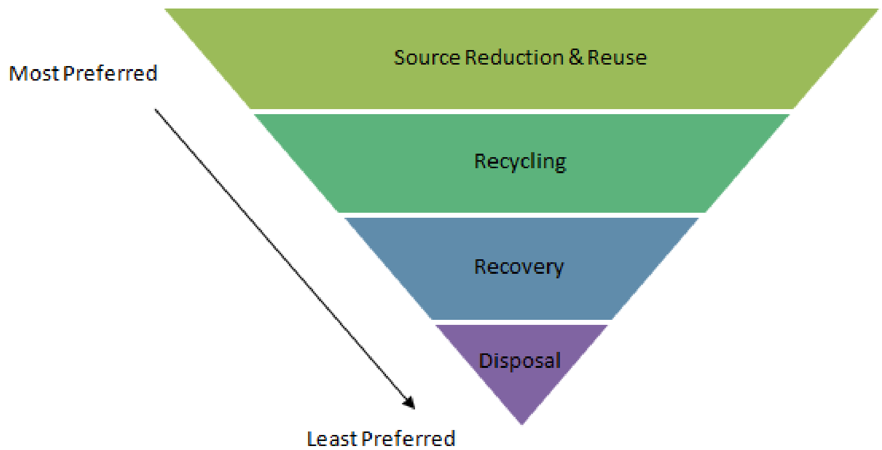

Figure 1: Waste Management Hierarchy

The US EPA's waste hierarchy defines the following waste management options, in order of preference:

1. Source Reduction & Reuse, for example reusing or donating, product re-design, or reducing packaging
2. Recycling/Composting – recycling of materials otherwise considered waste through collection, sorting, processing into new raw materials, and re-manufacturing into new products; or composting of organic waste e.g., food waste or yard trimmings
3. Energy Recovery – conversion of waste into heat, electricity or fuel (waste-to-energy) including combustion, gasification, pyrolization, anaerobic digestion, and landfill gas recovery
4. Treatment & Disposal – disposal landfills meeting stringent design, operation, and closure requirements; methane gas may be collected and used as fuel.[1]

Given this complex landscape of waste management options, the Healthcare Plastics Recycling Council (HPRC) sought to understand how recycling fits into the larger context of waste management options and whether and when advancing recycling makes sense from an environmental perspective. The HPRC conducted a literature review of life cycle assessment (LCA) studies comparing the environmental impacts of recycling to other waste management options. This paper presents the

[1] U.S. Environmental Protection Agency, "Non-Hazardous Waste Management Hierarchy."

different types of waste management for plastics and their advantages and disadvantages from an environmental perspective as well as the general observations of the literature review including how recycling compared to the other waste disposal methods and the critical parameters that influenced study results.

The focus of this paper is on the different waste management options and their LCA derived environmental impacts, rather than the economic or technological viability in various regions or for very specific applications. It applies learnings from these studies, which generally address mixed plastics in municipal waste, to US healthcare plastics. It aims to inform waste management decision makers at healthcare facilities, who must balance environmental as well as economic and practical considerations, on the environmental impacts of various waste management options. Note that while healthcare plastics may be recycled into other plastic products, they are unlikely to be recycled full circle back to the healthcare industry particularly because of the traceability and chain of custody requirements of materials that the FDA requires for materials to be manufactured into many medical products.

Plastics Waste Generation and Recycling

The US generated 251 million tons (U.S. short tons) of municipal solid waste (MSW) in 2012.[2] 34.5% of it was recycled or composted and 11.7% was combusted for energy recovery.[3] Achieving much higher rates of recycling, composting, and energy recovery is possible, as demonstrated by a number of European countries.[4,5] Austria and Germany, for example, have recycling and composting rates of higher than 60%, and send nearly the rest of their waste to incineration with energy recovery.[6,7]

Generation of plastics waste in the US has been steadily increasing over the years, from about one million tons in 1960 to nearly 32 million tons in 2012. In 2012 plastics represented 13% of total generated waste in the US.[8] Though the vast majority of discarded plastics were thermoplastic resins that are theoretically recyclable, only 9% of plastic waste was recycled (see Figure 2).[9] The amount recycled included 880 thousand tons of PET and 570 thousand tons of HDPE.[10]

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[2] U.S. Environmental Protection Agency. "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012." February 2014. http://www.epa.gov/epawaste/nonhaz/municipal/.
[3] Ibid.
[4] United Nations Environment Programme. "Guidelines for National Waste Management Strategies: Moving from Challenges to Opportunities."
[5] Ted Michaels. "The 2010 ERC Directory of Waste-to-Energy Plants." *Energy Recovery Council*. December 2010. http://www.energyrecoverycouncil.org/userfiles/file/ERC_2010_Directory.pdf
[6] United Nations Environment Programme. "Guidelines for National Waste Management Strategies: Moving from Challenges to Opportunities."
[7] Michaels. "The 2010 ERC Directory of Waste-to-Energy Plants."
[8] U.S. Environmental Protection Agency. "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012."
[9] Ibid.
[10] U.S. Environmental Protection Agency. "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2012." February 2014. http://www.epa.gov/solidwaste/nonhaz/municipal/pubs/2012_msw_dat_tbls.pdf.

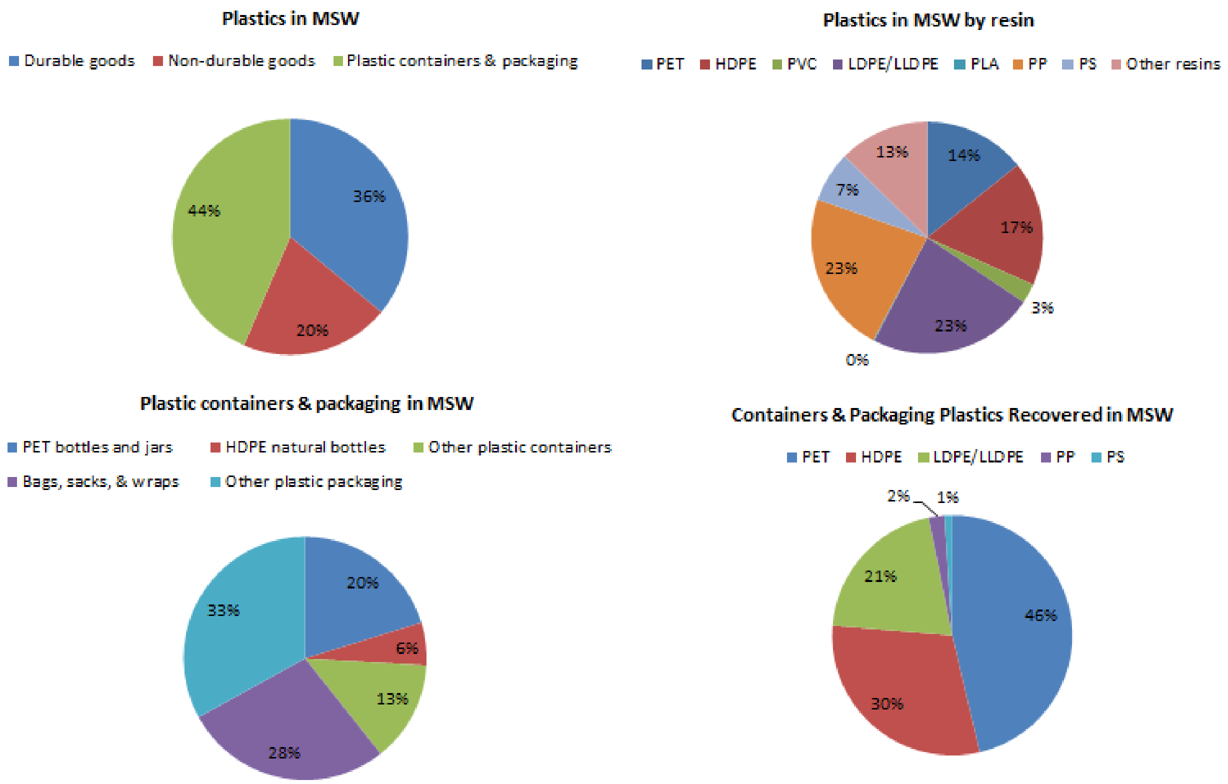

Figure 2 Plastics in Products in MSW, 2012[11]

US healthcare facilities generated 29.3 pounds of waste per bed per day in 2013[12], or approximately 13,500 tons of waste per day,[13] most of which is being disposed of in landfills or by incineration. It is estimated that between 20 and 25 percent of that can be attributed to plastic packaging and plastic products.[14] In addition, 85 percent of the hospital waste generated is non-hazardous, meaning free from patient contact and contamination.[15]

A 2012-2013 HPRC study of clinical recycling at Stanford Hospital and Clinics in nine clinical areas found that 110 tons of clean, dry packaging materials can be recycled in one year, representing a 29% diversion rate.[16] Plastics accounted for 75% of these materials. Common recyclable items included polypropylene Blue Wrap (~34 tons), film plastic and Tyvek® peel packs (including LDPE, PE, non-woven HDPE) (~29 tons), and rigid trays (including polypropylene, PET) (~16 tons).

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[11] U.S. Environmental Protection Agency. "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012."

[12] Practice Greenhealth. "2013 Sustainability Benchmark Report." 2013. https://practicegreenhealth.org/sites/default/files/upload-files/2013practicegreenhealthsustainabilitybenchmarkreport.pdf

[13] American Hospital Association. Fast Facts on US Hospitals. January 2015. http://www.aha.org/research/rc/stat-studies/fast-facts.shtml

[14] B. Lee, M. Ellenbecker, and R. Moure-Eraso. "Analyses of the Recycling Potential of Medical Plastic Wastes." *Waste Management* (2002): 461-470

[15] Terry Grogan. "Solid Waste Reduction in US Hospitals." *Hospital Engineering & Facilities Management* (2003): 88-91.

[16] Stanford Hospital & Clinics. "Clinical Recycling at Stanford Hospital & Clinics: A Healthcare Plastics Recycling Council Pilot Study." 2013. http://www.hprc.org.

Life Cycle Assessment

An LCA quantifies the environmental impacts of a product or service throughout its life cycle, from raw material extraction to end-of-life disposal (see Figure 4). The phases of an LCA as defined by ISO 14040 and 14044 are goal and scope definition, inventory analysis, impact assessment, and interpretation.[17] The life cycle inventory (LCI) phase of an LCA captures the resource inputs and the product, waste, or emission outputs for each process step in the life cycle. Results may focus on specific inventory categories such as water use or primary energy demand. The Life Cycle Impact Assessment (LCIA) phase quantifies potential environmental impacts based on the LCI such as global warming potential.

LCA aims to provide a holistic view of the environmental impacts of a product throughout its life cycle and to determine greatest sources of impact within the life cycle. It reveals trade-offs between different phases of the product life cycle or different types of potential environmental impacts.

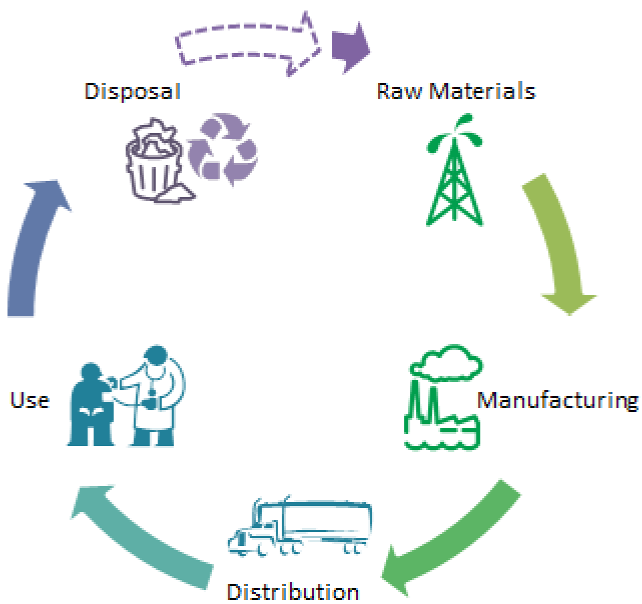

Figure 3: Product Life Cycle

There are widely used life cycle impact assessment methodologies such as TRACI from the US EPA and CML from the University of Leiden to calculate impact categories including global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and smog formation potential. These indicators represent the potential to impact the environment, and do not predict the actual fate and transport of individual emissions nor the damage to category endpoints e.g., damage to coral reefs. Characterization models for other impact categories are not as well developed or earlier in development, such as human and eco-toxicity and effects on land use and biodiversity.

[17] ISO. "ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines." 2006.

An LCA is based on primary data e.g., a manufacturer may collect data on its own operations, and secondary data e.g., from literature or LCA databases. An LCA may be limited by availability of primary data or of secondary data that is representative of the true population, with appropriate geographical and technology coverage. While an LCA may evaluate the potential environmental impacts of different scenarios, it does not typically address their economic feasibility or implications to human or animal labor.

LCA Studies Reviewed

The HPRC conducted a literature search for waste management LCA studies and reviewed 17 out of about 50 studies identified (see Table 1 below and Table 2 in Results of LCA Comparisons). The selection criteria for the studies reviewed included factors such as the age of the article, quality of article (e.g., peer reviewed journal article), and types of waste management options and waste streams, all factors perceived to be particularly relevant. Most of the papers reviewed were journal articles presenting LCA or LCI studies, or reviews of studies. Since there were not many US studies available, the majority of papers were for European regions, typically covering general household waste or waste for recycling for a country, state, or municipality. These waste streams include mixed plastics, and analyze various types of plastics, most commonly PET, PE, and HDPE. Disposal methods assessed in these papers included recycling back to polymer (mechanical recycling); recycling to feedstock, monomer, or other products (like pallets); incineration with energy recovery; and landfill.

Table 1: Metrics about Studies Reviewed

Number reviewed	17
Publication type	15 journal articles (one LCA divided into two articles); 1 report; 1 conference
Method	11 LCA or LCI; 5 LCA Review studies; 1 technology review
Region	11 Europe; 4 North America; 1 Australia; 1 US/Europe
Year	3 2010-2013; 9 2005-2009; 4 2000-2004; 1 1996
Breadth	Typically a country, state, or municipality; 1 industry specific (automotive)
Impact and inventory categories	Reviews: Vary from inventory only to multiple impact categories. Acidification, global warming, and eutrophication are repeated impact categories. Original LCAs: 2 multiple inventory emissions reported; 2 inventory only; most included energy, carbon dioxide, greenhouse gases, or global warming potential; 3 acidification potential; 2 eutrophication potential, ozone depletion potential, or some type of toxicity. Cost: 8 included some kind of cost or economic analysis.
Materials	Most cover household waste or waste for recycling in general, i.e., mixed plastics. The studies differ in which plastic types they address. PET, PE, and HDPE are most commonly analyzed.
Disposal methods	16 included recycling back to polymer, 4 recycling to feedstock, 1 recycling to monomer, at least 1 recycling to other products (like pallets, fences); 12 incineration with energy recovery; 12 landfill (some with, some without energy recovery)

For recycling back into a polymer resin, generally the scope of the study includes the environmental burden of recycling (collection, sorting, and processing) and then an offset (credit) for the production of the virgin resin avoided by providing material from recycling. This offset may even result in a net benefit of recycling, if the credit is higher than the impacts from collection and processing. Patel et al. also examined recycling plastic into a product that is usually made out of another material, such as pallets or fences, so the offset is not for virgin plastic.[18] For incineration with energy recovery in the form of electricity and steam, there is an environmental burden from combustion emissions (and possibly collection) and an offset for the energy generation it replaces, which varies in the studies (electricity grid mix, electricity from coal, district heating mix, district heating from wood, etc.).

A common life cycle inventory category covered by the studies is energy, a measure of the total energy required throughout the life cycle stages included, also known as primary energy demand.

A few examples of impact categories addressed in the studies include

- Global warming potential (climate change), a calculation of the potency of greenhouse gas emissions such as carbon dioxide and methane relative to carbon dioxide (carbon dioxide equivalents)
- Acidification potential, the introduction of acidifying substances to the environment, which may cause acid rain and damage to the environment and human-built structures
- Eutrophication potential, the release of nutrients to water bodies e.g., from fertilizer run-off, which may result in excess plant growth, causing death of aquatic animals from lack of oxygen

Waste Disposal Methods

Mechanical Recycling Back to Polymer

Plastic waste may be recovered and mechanically processed for use in the manufacturing of plastic products. Plastic waste is collected and sorted, and mechanically processed by recyclers into materials that can be reused to make other plastic products. Steps may include grinding, washing, separating and sorting, drying, re-granulating and compounding.[19] Mechanical recycling applies most broadly to thermoplastics, which can be re-melted and re-processed into products e.g., by extrusion or molding.

Single-polymer plastic streams are the most straightforward to recycle because recycling processes can be conducted without concern for immiscibility issues (where the polymers separate, similar to separation that occurs with mixtures of oil and water). The physical and mechanical properties of a single-polymer recycled resin can be generalized as roughly the “average” amongst the various grades of scrap that were processed together. Additionally, blends of compatible materials that may be processed together may also be mechanically recycled. For example, polyolefinic blends such as polypropylene and polyethylene, two of the major types of plastic likely to be recycled from hospitals, have very good mechanical properties, especially in the presence of copolymers and other compatibilizing agents.[20,21] Certain miscible polymer blends, such as PPO-PS blends (mixed electronic plastics and PS from other sources), PET/PBT, and even some upcycling of recycled PET to

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[18] M. Patel et al. "Recycling of plastics in Germany." *Resources, Conservation and Recycling*. 29, 1-2 (2000): 65-90.
[19] Plastics Recyclers Europe. Mechanical Recycling. http://www.plasticsrecyclers.eu/mechanical-recycling.
[20] S. Bertin and J.J. Robin. “Study and characterization of virgin and recycled LDPE/PP blends.” *European Polymer Journal* 38 (2002) 2255-2264.
[21] J.W. Teh, A. Rudin, and J.C. Keung,. “A review of polyethylene-polypropylene blends and their compatibilization.“ *Advances in Polymer Technology*. 13 (1994) 1-23.

PBT, have no issue of incompatibility. There are also certain techniques, commercially practiced, that utilize the properties of two different materials, like coextrusion to make fiber reinforcements for structural strength recycling practices.[22]

What can and cannot be recycled together depends on the end use requirements, even for various products that are made from the same plastic but used different original grades. For example, not all grades of PP can be blended together to blow mold a product with a thin wall and more intricate shape, nor could all grades be blended together to make a drape type product. Injection molding of components with coarse features and few mechanical strength requirements tends to be more forgiving.

There are also differences in material recovery facilities (MRFs) as well as the practices and capabilities of recyclers across the country that impact what kinds of combinations of plastics can be processed together.

The main challenges for mechanical recycling are heterogeneity and contamination. As explained by Al Salem et al, "The more complex and contaminated the waste, the more difficult it is to recycle it mechanically. Separation, washing and preparation of [plastic solid waste] are all essential to produce high quality, clear, clean and homogenous end-products. One of the main issues that face mechanical recyclers is the degradation and heterogeneity of [plastic solid waste]."[23]

Technology improvements in the recycling process, such as increasing the throughput of automated sorting machines, or by materials producers, such as using additives to improve the properties of recycled content plastics, may make more recycling options economically viable. SONY recently announced its commencement of external sales of a flame resistant polycarbonate with up to 99% recycled polycarbonate content,[24] based on new technologies for recycling and for the recycled material. Previously, flame-retardant recycled polycarbonate plastic had about 55% recycled content.

Feedstock Recycling

Feedstock recycling is one of the newer methods to recycle plastics. Sometimes also referred to as chemical recycling, feedstock recycling can be defined as attempting to recover the basic raw materials (monomers) from the plastic. These raw materials can then be reused in various chemical and industrial processes.

There are too many feedstock recycling technologies to review here but some examples include the following: Gasification converts mixed plastics into synthesis gas (syngas) which can be used to produce electricity or various chemicals.[25] Metal blast furnace processes can use mixed plastics in place of fossil fuels to reduce oxidized metals to pure metal.[26] Thermolysis

[22] Jan H. Schut. "Entrepreneur Puts Mixed-Polymer Recycling On Track to Success." *Plastics Technology*. May 2003. http://www.ptonline.com/articles/strategies---may-2003

[23] S.M. Al-Salem, P. Lettieri, and J. Baeyens. "Recycling and recovery routes of plastic solid waste (PSW): A review." *Waste Management* 29 (2009): 2625-2643.

[24] Sony. "Sony commences external sales of SORPLAS™ flame-retardant recycled plastic material that achieves high durability and heat resistance, and comprises up to 99% recycled content." 8 4 2014. http://www.sony.net/SonyInfo/News/Press/201408/14-073E

[25] Gershman, Brickner & Bratton, Inc. "Gasification of Non-Recycled Plastics from Municipal Solid Waste in the United States." *American Chemistry Council*. September 2013. http://plastics.americanchemistry.com/Sustainability-Recycling/Energy-Recovery/Gasification-of-Non-Recycled-Plastics-from-Municipal-Solid-Waste-in-the-United-States.pdf .

[26] PlasticsEurope. "Plastics convert iron ore to steel." September 2009. http://www.plasticseurope.org/Document/plastics-convert-iron-ore-to-steel.aspx?Page=DOCUMENT&FolID=2.

of olefinic plastics like polyethylene and polypropylene yields mixed hydrocarbon fuels.[27] And polyethylene terephthalate can be broken down into its monomers through various process technologies.[28] For example, modified polybutylene terephthalate co-polymers made from polyethylene terephthalate water bottles through a chemical depolymerization process.[29]

Incineration with Energy Recovery

Waste incinerators are furnaces for burning waste and there are a number of types that are in current use around the world, ranging from primitive burn piles and barrels to highly sophisticated facilities that may involve fluidized beds and produce electricity. Open burning methods are used more commonly in rural areas and less developed parts of the world. In an incineration facility, the use of grates, rotary kiln chambers, or fluidized beds optimize the introduction of waste materials and gases in the burn zone for more efficient combustion. Incinerators with energy recovery systems generate steam that can be used either directly in municipal heating systems or to rotate turbines to generate electricity. The efficiency of energy generation of these systems varies greatly depending on the technology utilized in the incineration facility. Incineration facilities also have flue gas cleaning systems to reduce the amount of pollution and particulates that are released. The effectiveness of these systems also varies significantly based on the technologies used.

Incineration with energy recovery covers a few distinctively different systems:

1. General solid waste incineration systems where the energy is recovered as electricity or as a combination of electricity and heat, or as heat alone.[30] The latter case includes municipal systems where wastes are burned and the heat generated is utilized in a heating system for multiple municipal homes, buildings and other structures.[31] In such systems, the waste typically replaces another material that was previously being utilized to provide district heating, such as wood, coal, or oil.[32,33,34]
2. Combustion of plastic waste as part of a solid recovered fuel in cement kilns and related industrial facilities [Lazarevic, Aostin, Bulcet, Brandt].

Systems of both types can operate with significantly different efficiencies and replace different types of energy sources. In the reviewed articles, most of the replacement sources were fossil-fuel based, such as oil and coal. For one case, wood was a partial source. In no cases were the original sources nuclear, solar, or wind power.

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[27] Achyut K. Panda, R.K. Singh, and D.K. Mishra. "Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products—A world prospective." *Renewable and Sustainable Energy Reviews* 14, no. 1 (January 2010): 233-248.
[28] Leian Bartolome, Muhammad Imran, and Bong Gyoo Cho. "Recent Developments in the Chemical Recycling of PET." In *Material Recycling - Trends and Perspectives*, Edited by Dimitris S. Achilias, 65-84. Rijeka: InTech, 2012.
[29] P Argawal et al. US Patent 8,088,834.
[30] David Lazarevic et al. "Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective." *Resources, Conservation and Recycling* 55 (2010): 246-259.
[31] Kristina Holmgren and Dag Henning. "Comparison between material and energy recovery of municipal waste from an energy perspective: a study of two Swedish municipalities." *Resources, Conservation and Recycling* 43 (2004): 51-73.
[32] Ibid.
[33] Hanna Merrild, Anna W. Larsen, and Thomas H. Christensen. "Assessing recycling versus incineration of key materials in municipal waste: The importance of efficient energy recovery and transport distances." *Waste Management* 32, no. 5 (2012): 1009-1018.
[34] Vollrad Wollny et al. "Feedstock Recycling vs. Incineration of Plastic Packaging in Germany." *Journal of Industrial Ecology* 5, 3 (2001): 49-63.

The life cycle assessments that are reviewed cover currently used “modern” incineration systems with energy recovery with varying efficiencies and pollution capture technology, and also utilize different assumptions for the material mixture being burnt.

Landfill

Landfills include any site where waste is dumped and confined over a relatively small area and compacted to reduce volume as much as possible. The wastes are then covered by soil in order to bury them. Liquids in the waste may move away from the original deposition site, due to a combination of gravity and rainfall, to produce a “leachant” that has also picked up chemical characteristics of the other wastes that were in its path. Wastes may also decay and produce gases such as methane, which may be captured and used to generate electricity.

Landfills in the US are primarily regulated by state, tribal, and local governments.[35] Additionally, federal regulations such as location restrictions, composite liners requirements, leachate and removal systems, and groundwater monitoring requirements aim to protect the environment from contaminants.[36]

Landfills that have been studied with LCA techniques include engineered landfills that extract leachates and harvest landfill gases[37] and landfills with and without energy recovery.[38] For the studies reviewed in Lazarevic, et al., the plastic waste stream, only, was considered in landfills, even though it was one part of the general municipal solid waste stream. In the study by Morris, mixed wastes including plastic were studied.

Results of LCA Comparisons

The majority of LCA studies reviewed show mechanical recycling of waste plastics has a lower environmental impact than disposal to landfill or incineration, even with energy recovery (see Table 2 and Table 3). The studies assessed a variety of inventory and impact categories. Energy and global warming potential were the most common categories assessed. Feedstock recycling also performed better than landfill or incineration. Incineration of waste plastics with energy recovery was generally found to have lower energy demand than landfill, but not necessarily lower greenhouse gas emissions.

Table 2: LCA Results by Study

Study	Review (#)* or Original	Impact/Inventory Categories**	Results***
Björklund and Finnveden 2005	Review (10)	Energy, GWP	M < I
Denison 1996	Review (4)	Energy, air & water emissions, waste	M < I; M < L

[35] U.S. Environmental Protection Agency. “Landfills.” 1 10, 2014. http://www.epa.gov/waste/nonhaz/municipal/hierarchy.htm.
[36] Ibid.
[37] Lazarevic et al. "Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective.”
[38] Jeffrey Morris. "Comparative LCAs for Curbside Recycling Versus Either Landfilling or Incineration with Energy Recovery." *The International Journal of Life Cycle Assessment* 10, no. 4 (2005): 273 – 284.

Duval and MacLean 2007	Original	GWP	M < L
Eriksson et al. 2005	Original	Energy	M < I < L
Finnveden et al. 2005, Moberg et al. 2005	Original	Energy, GWP	M < I < L
Franklin Associates 2011	Original		Mechanical recycling only
Holmgren and Henning 2004	Original	Energy	M < I
Hopewell et al. 2009	Review (10)	Energy, GWP	M < I; M < L
Lazarevic et al. 2010	Review (10)	Multiple inventory and impact categories	M < F < I < L, except for GWP, where L < I
Merrild et al. 2012	Original	GWP, AP, nutrient enrichment, photochemical ozone formation	M, I unclear
Morris 2005	Original	Energy, GWP, AP, EP, disability adjusted life year losses from emission of criteria air pollutants, human toxicity and ecological toxicity	M < I; M < L
Olofsson et al. 2005	Review (12)	GWP, AP, EP	GWP: M < I < L (majority) AP: M < I < L (mostly) EP: unclear
Patel et al. 2000	Original	Energy, CO_2	M < I; F < I
Perugini et al. 2005	Original	Energy, GWP, water, air & water emissions, waste	M < F; M < I; M < L
Ross and Evans 2003	Original	Energy, GWP, photochemical oxidant precursors	M < L
Wollny et al. 2001	New analysis of an LCA	Energy, CO_2, AP	CO2: F < L < I AP: F < L; I < L Energy: F < L

* # = Number of publications reviewed. There may be multiple case studies in one publication.
** GWP = global warming potential; AP = acidification potential; EP = eutrophication potential
*** < indicates lower impact (better); M = mechanical recycling; F = feedstock recycling; I = incineration with energy recovery; L = landfill

Table 3: LCA Results Summary*

	Feedstock Recycling	Landfill (with or without gas recovery)	Incineration	Mechanical Recycling
Energy	😐	☹	😐	☺
Global Warming Potential	😐	☹	☹	☺

* ☺ Best (least environmental impact); 😐 Second best; ☹ Worst

An analysis conducted by HPRC of disposal of polypropylene and polyethylene terephthalate modeled in the LCA Software GaBi 6 using average life cycle inventory profiles from the GaBi 6 Database also showed that mechanical recycling was superior for primary energy demand and global warming potential compared to incineration with energy recovery and to landfill (see Appendix A). Mechanical recycling of polypropylene had a lower eutrophication potential but a higher acidification potential than incineration with energy recovery while this result was reversed for polyethylene. Consistent with the literature review, landfill performed better than incineration with energy recovery for global warming potential and worse for energy demand. Landfill was also the worst option for acidification potential and eutrophication potential.

Many of the studies did not address the substitution ratio of recycled to resin to virgin resin when calculating the credit for virgin resin production avoided, which would take into account the quality and possible applications of the recycled resin produced compared to virgin resin. For example, the WRATE tool credits one metric ton of secondary HDPE with the avoidance of extraction and production of 825 kg of virgin HDPE.[39]

For one study comparing recycling to incineration, the results depended on the level of energy recovery at the incineration plant, the system boundaries chosen and which impact category was in focus.[40] Another study was a review study that found that for global warming potential the majority of studies showed recycling as better than incineration.[41] Results in two studies were too close to conclude whether recycling was better than incineration while a third showed recycling as unfavorable when wood palisades were substituted. For acidification potential, recycling was better for many cases but not all. Eutrophication potential results were inconclusive with some studies showing recycling as best, some very close in results, and some showing incineration was better.

The environmental impacts of incineration systems seem less dependent on organic contamination than material recovery for recycling. When there is organic contamination, the environmental impact benefits for recycling diminish very significantly.[42]

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[39] Jonna Mehhoff Fry et al. "Life cycle assessment of example packaging systems for milk." *WRAP.* January 2010. http://www.wrap.org.uk/sites/files/wrap/Final%20Report%20Doorstep%2029%2001%2010%20%282%29.pdf.
[40] Hanna Merrild, Anna W. Larsen, and Thomas H. Christensen. "Assessing recycling versus incineration of key materials in municipal waste: The importance of efficient energy recovery and transport distances." *Waste Management* 32, 5 (2012): 1009-1018.
[41] Mattias Olofsson, Johan Sundberg, and Jenny Sahlin. "Evaluating waste incineration as treatment and energy recovery method from an environmental point of view." 13th North American Waste to Energy Conference. Orlando, Florida: ASME, 2005. NAWTEC13-3168.
[42] Lazarevic et al. "Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective."

Environmental impact differences between feedstock recovery and incineration systems utilizing solid recovered fuel for cement kilns are not as clear.[43]

Some feedstock recycling methods offer the ability to handle mixed plastics and plastics that have been contaminated with other materials like food, soil, and metals. Where sorting of materials due to technical, logistical, or market constraints is impractical, feedstock recycling can reduce the environmental impact of plastic waste that would otherwise be landfilled.

The following summarizes parameters that influenced results of these studies.

- Type of material that recycling replaces: When the recycled plastic substitutes for a non-plastic product (wood palisades, pallets, fences, etc.) instead of virgin plastic, incineration with energy recovery was better than recycling.[44,45]
- Virgin material substitution ratio: One study noted results for comparing mechanical recycling to incineration with energy recovery were sensitive to the virgin material substitution ratio.[46]
- Contamination: In one study, results for comparing mechanical recycling to incineration with energy recovery were sensitive to the amount of organic contamination.[47]
- Efficiency of energy recovery of incineration: According to Merrild et al., incineration may be a better choice than mechanical recycling for global warming and ozone formation in highly efficient incinerators, but the benefit was small.[48]
- Technology: Especially important when comparing feedstock recycling to mechanical recycling or to incineration.[49]
- Type of energy that incineration replaces: For incineration with energy recovery, the amount of benefit is influenced by what type of energy it replaces (electricity from coal, electricity grid mix, heating from wood, etc.)
- Distance: Merrild et al concluded with the right means of transport, recyclables can in most cases be transported long distances.[50]
- Volume: According to Merrild et al 2012, recycling of some of the material fractions can only contribute marginally in improving the overall waste management system taking into consideration their limited content in average Danish household waste.[51] Additionally, Patel 2000 showed cost per ton of recycling decreases as volume increases.[52]
- Impact or inventory category: The conclusions are not always the same for different environmental impact categories

[43] Ibid.
[44] Olofsson et al. "Evaluating waste incineration as treatment and energy recovery method from an environmental point of view."
[45] M Patel et al. "Recycling of plastics in Germany." *Resources, Conservation and Recycling*. 29, 1-2 (2000): 65-90.
[46] Lazarevic et al. "Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective."
[47] Ibid.
[48] Merrild et al. "Assessing recycling versus incineration of key materials in municipal waste: The importance of efficient energy recovery and transport distances."
[49] Lazarevic et al. "Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective."
[50] Merrild et al. "Assessing recycling versus incineration of key materials in municipal waste: The importance of efficient energy recovery and transport distances."
[51] Ibid.
[52] Patel et al. "Recycling of plastics in Germany."

Economics

Mechanical recyclers purchase the input materials based on market value, which should be higher than the cost of collecting and sorting the material.[53] Converters often pay a lower price than the price of virgin resin due to perceived degradation of quality.[54] For example, in the EU market the price of recovered natural HDPE bottles in December 2010 was £303 per metric ton while virgin HDPE was £1070 per metric ton.

Estimated revenue from the recycling industry is $236 billion in the US in 2007 and at least EUR 60 billion in the EU countries in 2008.[55] The world market for municipal waste is worth an estimated $410 billion per year but only a quarter of the 4 billion tons of municipal waste produced each year is recycled.[56]

Three studies (Holmgren 2004, Wollny 2001, and Duval 2007) showed recycling was more costly than incineration. Morris 2005 calculated that the societal benefits from avoided pollutants outweighed the cost of curbside collection.

In order to achieve higher levels of recycling, Swedish federal policy requires material recovery (and recycling) for packaging, newspapers, used cars, tires, electric and electronic devices. This is done at the household level, with mandatory source separation for hazardous waste, batteries, light bulbs, electronic wastes (for special disposal), and for metals, glass, plastic, paper, newspaper, and food waste for recycling [Avfall Sverige].[57] Sweden also taxes waste incineration with energy recovery in order to help even out with the economics for material recovery and for biological treatments for waste [Holmgren, Henning].

Feedstock recycling does cost more than alternative recycling methods such as incineration with energy recovery and mechanical recycling. While further technology development will reduce costs faster for feedstock recycling than the others, potential cost equality appears a long way out. Feedstock recycling facilities must be designed to target specific waste streams. Availability and distance of suitable waste sources are critical factors in assessing costs and overall environmental impact. Whereas some processes such as syngas production can use mixed plastics, higher value processes such as those recovering monomers require higher quality sorted plastics.

Discussion and Applicability for Healthcare Plastics

Overall, the LCA studies reviewed concluded that mechanical recycling of waste plastics has a lower environmental impact than other disposal options, particularly due to the benefits of avoiding virgin plastic production. There were exceptions, including the analysis done by HPRC that showed incineration with energy recovery was better than recycling for a couple of specific resins and impact categories (see Appendix A). The findings confirm the waste hierarchy guidance to pursue mechanical recycling as the most preferred waste management option after source reduction and re-use as a strategy for environmental protection and natural resource conservation. The demand for recycled resins, low plastic waste recycling rates, and ongoing technological advances suggest that there is potential for mechanical recycling to grow.

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53 Plastic Recyclers Europe. “Mechanical Recycling.”
54 Ibid.
55 United Nations Environment Programme. Municipal solid waste: Is it garbage or gold? October 2013. http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=105.
56 Ibid.
57 Avfall Sverige. “Towards a Greener Future with Swedish Waste-to-Energy: The World’s Best Example.” http://www.avfallsverige.se/fileadmin/uploads/forbranning_eng.pdf.

A number of factors influence the study results and the situations best suited for mechanical recycling. Mechanical recycling is most easily implemented for non-contaminated, homogeneous waste streams. The possibility for recycled plastics to be used in a product depends on the application. The LCA studies do not explore the particular applications of the recycled plastic. LCA studies provide a useful tool for quantifying various environmental impacts of different disposal options, but must be taken in the context of the underlying data quality, assumptions, and scope.

Where sorting of materials due to technical, logistical, or market constraints is impractical, feedstock recycling can reduce the environmental impact of plastic waste that would otherwise be landfilled. Some feedstock recycling methods offer the ability to handle mixed plastics and plastics that have been contaminated with other materials like food, soil, and metals. Feedstock recycling is not widely employed and will improve with further technology developments.

The LCA studies also show that incineration with energy recovery may have environmental advantages over landfill in some cases, but not all. For example in some cases the global warming potential of landfill was lower than of incineration with energy recovery. The efficiency of the incinerator is a key factor affecting the impact of incineration with energy recovery.

In Sweden, separation and recycling are required prior to use of incineration with energy recovery systems. In Germany, precise sorting is also considered a prerequisite for waste materials entering incineration and energy recovery systems [Umwelt Bundes Amt].[58] In the US, a number of the waste-to-energy incineration facilities have had to seek additional waste from surrounding areas as recycling capabilities have increased [Clark County Solid Waste Management Plan].[59] In all of these cases, the waste hierarchy, where environmental impacts have been considered, has influenced the overarching policies around waste.

This paper investigates literature available on Life Cycle Assessment of various disposal options, which was primarily on municipal waste, with the goal of informing the HPRC on the value of increasing healthcare plastics recycling. Extrapolating to healthcare plastics, the findings suggest that increasing healthcare plastics recycling would have benefits from an environmental perspective, especially for higher volume, non-contaminated waste streams, and where recycling infrastructure is available. The recycling rates and waste-to-energy rates of municipal waste vary across the country (see Figure 4 through Figure 6). Pennsylvania stands out for a high volume of staffed beds, a high rate of recycling, and the presence of incineration facilities.

Healthcare plastics waste may differ from municipal plastics waste in a number of ways that affect recycling:

- Resin: Municipal waste is high in polyethylene and polyethylene terephthalate (54% of plastics waste generated and 68% of plastics waste recovered) (EPA 2012) while healthcare plastics have a higher polypropylene content
- Type: Municipal waste may have more rigid plastics than healthcare plastics; only 23% of container and packaging waste recovered in 2012 were flexible bags, sacks, and wraps (EPA 2012)
- Separation: Curbside recycling programs for municipal waste tend to be single source. In an industrial or institution environment, there may be more separation to gain financial returns. An estimated 55-65% of municipal waste

[58] Umwelt Bundes Amt. Waste Incineration and Waste Prevention: Not a Contradiction in Terms. July 2008. http://www.umweltbundesamt.de.
[59] Clark County. "Chapter 9, Energy Recovery and Incineration." In *Clark County Solid Waste Management Plan*. 2000.

recovered in the US in 2010 was from residential sources and 35-45% from industrial and institutional sources (EPA 2010).

- Cleanliness: A hospital environment may have cleaner, higher quality plastics waste streams than is possible at a consumer level.

While the findings suggest there would be environmental benefits to increasing healthcare plastics recycling, they also show there are a number of factors that affect the study results. This paper highlights general observations from a limited number of studies that vary in scope, geography, age, and data sources, and does not vouch for the quality of these studies. It is not a comprehensive review of the LCA or technical literature available. Further studies that are specific to healthcare plastics recycling in the US are needed to quantify the potential environmental impacts, identify the possible applications for recycled healthcare plastics, understand the parameters critical to the results, and find improvement opportunities.

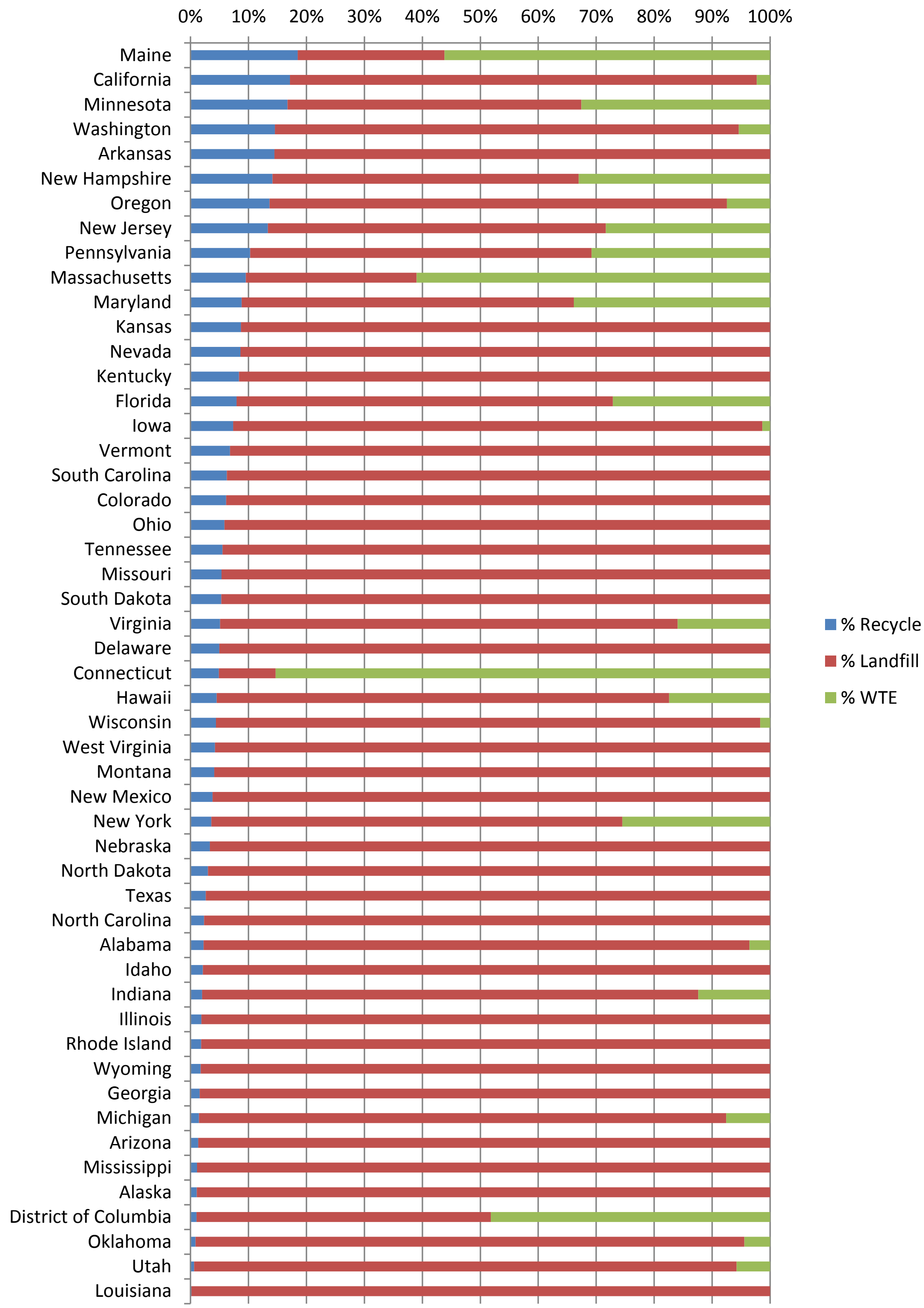

Figure 4: Recycling, Landfill, and Waste-to-Energy of MSW in 2011[60]

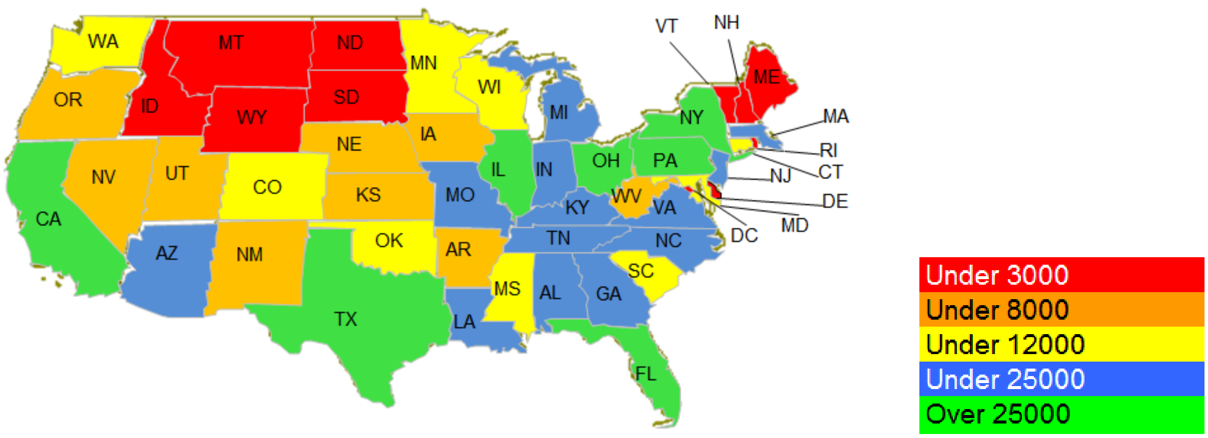

Figure 5: Staffed Beds in 2012[61]

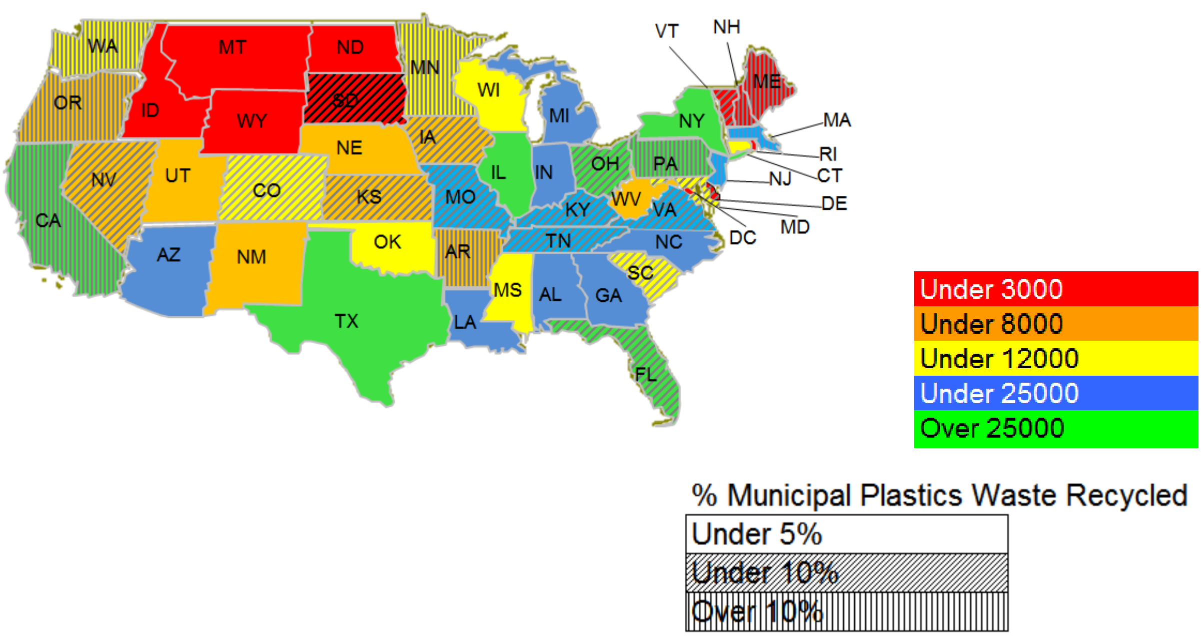

Figure 6: Staffed Beds in 2012 and % Municipal Plastics Waste Recycled in 2012

[61] American Hospital Directory. 2012. http://www.ahd.com.

Appendix A: HPRC Comparison of Potential Environmental Impacts of Plastic Waste Disposal

The following five waste treatment scenarios for disposal of 1 kg of polypropylene (PP) and 1 kg of polyethylene terephthalate (PET) in the US were compared:

- Mechanical recycling with credit for virgin granulate production
- Incineration including credits for energy recovery of electricity (US average grid mix) and steam (thermal energy from natural gas)
- Incineration including credit for energy recovery of electricity only (US average grid mix)
- Incineration without energy recovery
- Landfill (average landfill gas capture, combustion)

The scenarios were modeled in GaBi 6 Software and utilized the GaBi Database for backrgound data (see Table 2). The potential environmental impacts are calculated using the US EPA's impact assessment methodology TRACI 2.1. Results are shown for the following inventory and impact categories (see Figure 5 and Figure 6):

- Primary energy demand (net calorific value)
- Global warming potential, excluding biogenic carbon (100 years)
- Acidification potential
- Eutrophication potential

Table 4 Datasets Used in Comparison

Category	Name	Region	Source
Recycling	Recycling of polypropylene (PP) plastic	US	PE International
	Recycling of polyethylene terephthalate (PET) plastic	US	PE International
Recycling credit, virgin granulate	Polypropylene granulate (PP)	US	PE International
	Polyethylene terephthalate granulate (PET)		
Incineration	Incineration of polypropylene	EU-27*	PE International
	Incineration of polyethylene terephthalate (PET)	EU-27*	PE International
Incineration energy recovery credit, electricity	Electricity grid mix	US	PE International
Incineration energy recovery credit, steam	Thermal energy from natural gas	US	PE International
Landfill	Landfilling of plastic waste	US	PE International

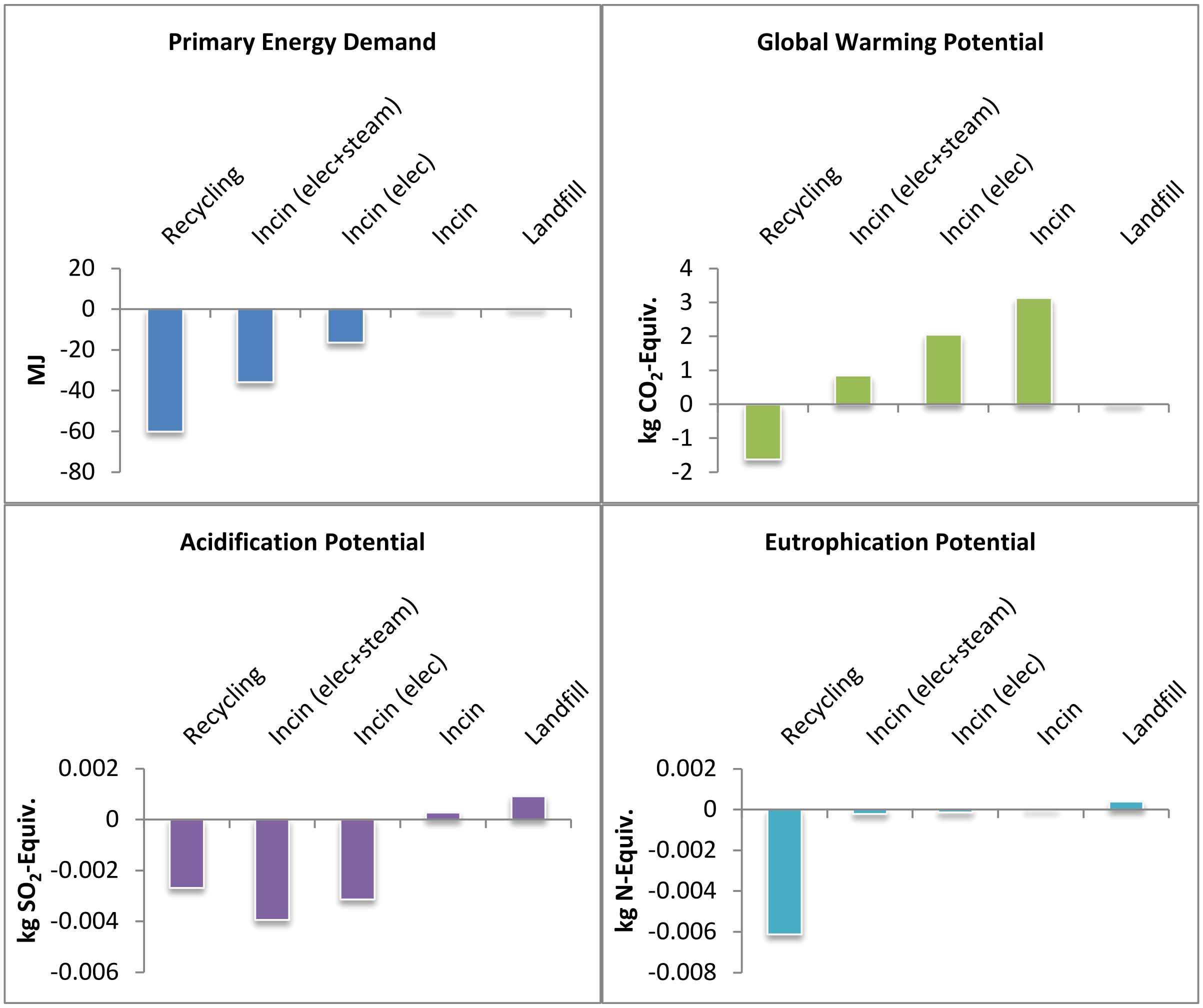

Figure 7: Comparison of Disposal Methods for 1 KG of Polypropylene Waste

Recycling, incineration, and landfilling processes all have an environmental impact. The credits applied for recycling or energy recovery have a "negative" environmental impact, representing an avoided burden of producing plastic granulate from virgin materials or of electricity or steam generation. The net result is negative when the credit outweighs the environmental impact for a given scenario. Three incineration scenarios are included to show the difference in environmental impact when both heat (steam) and electricity are recovered compared to when only electricity is recovered, or when there is no energy recovery.

Recycling has the lowest primary energy demand for both PET and PP, followed by incineration with avoided electricity and/or steam generation. These scenarios have a net negative total energy demand. Incineration without energy recovery and landfill have a small primary energy demand.

Recycling also has the lowest global warming potential and is net negative due to the avoided virgin plastic production. Landfill is the second lowest; for landfill, the plastic is sequestered in the ground (for a many, many years) and the gases generated are not released into the air.

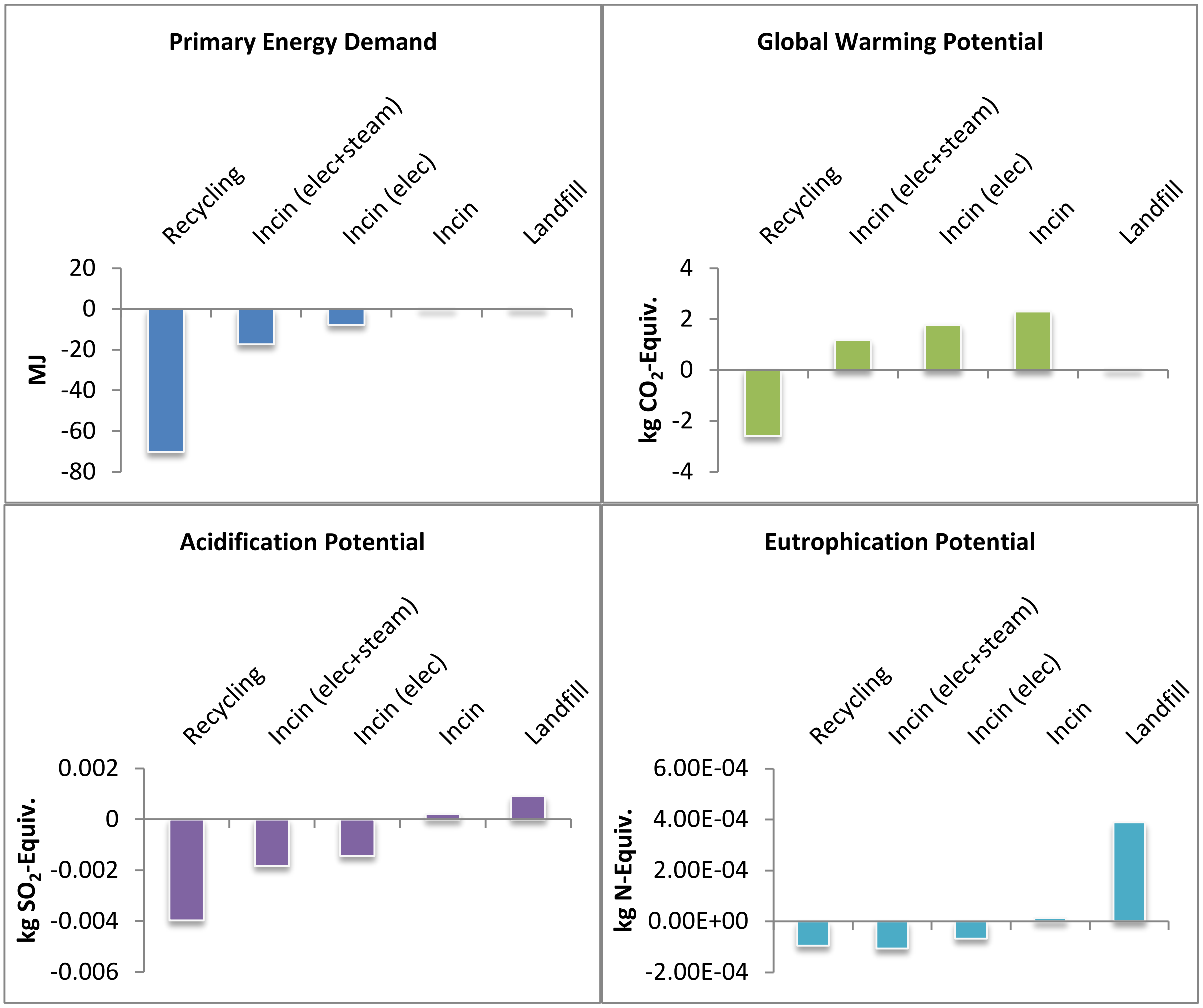

Figure 8: Comparison of Disposal Methods for 1 KG of Polyethylene Terephthalate Waste

Incineration of polypropylene with energy recovery has the lowest acidification potential, while for polyethylene terephthalate recycling was the best option. For eutrophication potential, incineration of polyethylene terephthalate with both electricity and steam recovery is slightly lower than recycling, while for polypropylene recycling was clearly the best option.

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