**Technical assessment for**

Household & Commercial RECYCLING

Sector: Materials

Agency Level: Municipal

Keywords: Recycling, Municipal Solid Waste Management, Zero Waste, Materials Recovery, Waste Diversion, Landfill, Circular Economy

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# Acronyms and Symbols Used

|  |  |
| --- | --- |
| AFR  EAP  ECA  GDP  GHG  HIC  ICI  IPCC  ISWM  Kg/capita/day  LCR  LIC  LMIC  MBT  MENA  METAP  MRF  MSW  mtCH4e  mtCO2e  OECD  PAHO  RDF  SAR  SWM  tCO2e  UMIC | Africa region  East Asia and Pacific region  Europe and Central Asia region  Gross Domestic Product  Greenhouse gas  High-income country  Industrial, commercial, and institutional  Intergovernmental Panel on Climate Change  Integrated solid waste management  kilograms per capita per day  Latin America and the Caribbean region  Low-income country  Lower middle-income country  Mechanical biological treatment facility  Middle East and North Africa region  Mediterranean Environmental Technical Assistance Program  Material recovery facility  Municipal solid waste  Million metric tons of methane equivalent  Million metric tons of carbon dioxide equivalent  Organisation for Economic Co-operation and Development  Pan-American Health Organization  Refuse–derived fuel  South Asia region  Solid waste management  Tons of carbon dioxide equivalent  Upper middle-income country |

# Executive Summary

Material recycling technologies that convert waste into valuable feedstock resources are coming into greater focus due to increasing volumes of waste generated globally. Recycling recovers materials which can be used in new products, thus reducing the amount of materials manufactured from virgin sources. Recycling waste has significant advantages of diverting waste from landfills and open dumps, including reducing land requirements for landfills. Using recycled materials as industrial feedstocks produces less greenhouse gas emissions than using conventionally produced materials from virgin sources. This study compares the financial feasibility and greenhouse gas reduction potential recycling of waste to the conventional practice of landfilling waste.

Several steps are required for effective recycling. First, it must be collected and transported to collection centers, then it needs to be sorted and categorized in mechanical-biological or recycling facilities, and then it needs to be treated, so that materials are recovered and ready for their second life. Waste is recycled only after it is sorted by material: metal, plastic, glass, textiles, wood, e-waste etc. in facilities for sorting. Often, sorted waste (including e-waste) is sold to scrap dealers which manage further sale of sorted waste for materials recovery. Recycling electrical and electronic equipment (e-waste) requires specialized recycling facilities, because dismantling and sorting this type of waste requires specialized technology, time, cost and procedures.

Types of waste which are not included in this study are compostable (organic) waste – assessed in the Composting model, paper – assessed in the Recycled Paper model, construction and demolition waste, ash, and street sweepings.. Recyclable waste which is considered in this study are metals, plastic, glass and “other”. Waste that is recyclable (as defined in this study) makes up around 37% of total municipal solid waste generated globally. Recycling rates are estimated on the regional level. This study shows current recycling rates (% of recyclable material as defined in this study that is recovered and recycled) of 62% (OECD90), 43% (Eastern Europe), 22% (Asia sans Japan), 22% (Middle East & Africa) and 12% (Latin America).

The potential for household and commercial recycling as a waste diversion from landfill solution depends on a decreased cost of this solution. Recycling is characterized by high operating costs which include costs of collection, transport, sorting waste, labor costs and others, and high capital costs due to costs of equipment and technology needed in mechanical-biological treatment and material recycling facilities. Greater implementation of recycling worldwide can be expected with the development of technology that would enable more efficient waste sorting and sorting at the source even before waste is collected.

Through the analysis conducted in this study, recycling has been found to be a beneficial waste treatment that results in annual emissions reduction of 11-13 Gt C02 by 2050. As recycling is currently adopted at only 43% globally, with an estimated regional maximum recycling rate of 70-80% in 2050, in this study future waste generation and waste composition are modelled, and several scenarios are developed. The emissions reduction potential of recycling has been determined through estimating emissions from conventional landfilling of recyclable waste and emissions that are avoided due to materials recovered from recyclable waste and used in place of virgin feedstocks.

With $150-170 billion US dollars of cumulative first cost and $30-37 billion US dollars net operating costs (these savings are largely created by the revenue generated from recovered materials) in the period 2020-2050, recycling requires large investments in equipment, technology and construction site development of a waste sorting facility (capital costs), but also results in high operating costs due to all different collection, sorting and transport processes which are necessary for waste recycling.

# Literature Review

## State of Municipal Solid Waste – Waste Generation, Composition and Waste Management Practices

According to Encyclopedia of Corporate Social Responsibility[[1]](#footnote-1), waste is any substance, material or object that is considered useless in terms of further deployment. Waste management is the procedure of monitoring and handling waste from collection, transport, treatment and processing, materials recovery and recycling, to final disposal of the remaining residual waste.

To develop and model recycling of municipal solid waste in the period between 2020 and 2050, first, waste composition must be established. Since not all types of waste are recyclable, a literature review is performed on different types of waste and waste management and treatment technology that is used to treat municipal solid waste.

Table : Synonyms, Definition and Types of Waste according to Encyclopedia of Corporate Social Responsibility

|  |  |
| --- | --- |
| Solid Waste Management - synonyms | Collecting; Final disposal of waste (rubbish, garbage, litter); Handling; Monitoring; Recovery; Recycling; Transporting; Treatment, Processing. |
| Definition of waste | Any substance or object which the owner wants to discard or is obliged to dispose, that is, materials that are useless in terms of further deployment. |
| Types of waste (agency level) | * Municipal waste (Household & Commercial) * Industrial waste * Hazardous waste (including biomedical and clinical waste) * Special hazardous waste (including radioactive waste, explosive waste, and waste from electrical and electronic equipment - WEEE) |
| Types of waste (source material, feedstock) included in the study | * metals * plastic * glass * other (wood and garden waste, textiles, rubber, bulky, WEEE and e-waste) |
| Types of waste (source material, feedstock) not included in the study | * organic (food waste) * paper, paperboard and cardboard |
| Types of waste - non-recyclable waste | - inorganic non-recyclable waste (construction and residual waste, ash, small amounts of waste from industry, street sweepings) |

Waste composition and waste generation rates[[2]](#footnote-2) are assessed to quantify amounts of metals, plastic, glass and other which are waste that is recyclable.

Waste management can be performed for solid, liquid, gaseous or hazardous, toxic, and radioactive substances and types of disposed waste. At the municipal level, individual and household recycling are altogether considered as residential recycling, e.g. recycling of Municipal Solid Waste(MSW). Commercial Recycling takes into account recycling of Industrial Solid Waste(ISW) and Waste from Electrical and Electronic Equipment –WEEE (e-waste). In some cases, the last step of recycling (recovery of materials) is performed at the same facilities as conventional virgin materials production..

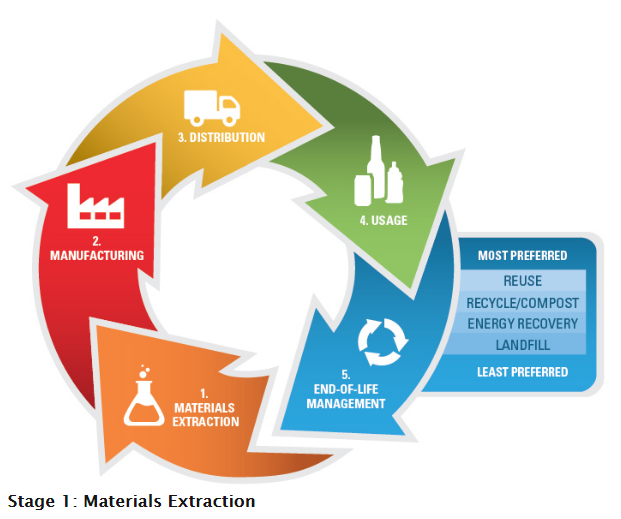


Figure 1: Conventional life cycle of materials (EPA 2016)[[3]](#footnote-3)

Even waste generated at industrial factories which manufacture products and goods from virgin materials are sent directly to the corresponding recycling and material recovery facilities that produce materials from virgin sources. In case of Industrial Solid Waste, there is no need for intermediary transport and recovery of materials in waste recycling facilities.

A small percentage of Industrial Solid Waste is non-recyclable inorganic waste (ash, street sweepings, ash from waste incinerators etc.) and liquid waste (water, oil, etc.) which are also not included in this study.

Solid waste management tends to promote proper storage, collection, transportation, treatment and disposal of waste with the aim to minimize risk to the environment and human health (Kassim, 2012)[[4]](#footnote-4). Discarded materials are collected, some are recycled or composted, and most are landfilled or incinerated (Hoornweg and Bhada-Tata, 2012)[[5]](#footnote-5). Actions which promote reuse, redesign and takeback of products before they are discarded are preferable over any other waste treatment options (Xevgenos et al. 2015). The order of waste treatment options, technologies and scenarios is called Zero waste hierarchy or Waste hierarchy.

Typical order of preferable waste management practices is waste management hierarchy, e.g. prevention, minimization of waste, reuse and recycling, recovery and disposal. Recycling waste management practice aims at increased recycling of products, components and materials.

Mostly waste generated by households has little or no negative environmental impacts if managed properly. Packaging waste is most prominent in solid waste generated by households. Hazardous Household Waste (in the category of WEEE) like batteries, and out-of-date medicine equipment are typically present in quite small quantities in household waste, but may cause serious environmental impacts (groundwater and soil pollution), fires or explosions.

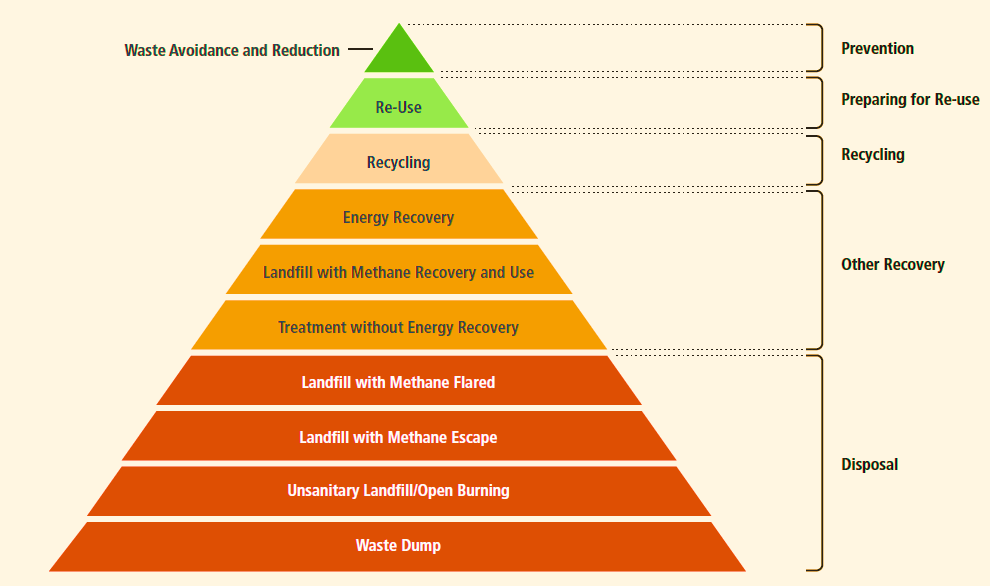


Figure 2: Waste management hierarchy. The priority order and color coding is based on the five main groups of waste hierarchy classification (Prevention; Preparing for Re-Use; Recycling; Other Recovery and Disposal) outlined by the European Commission (EC, 2008)[[6]](#footnote-6)

Municipal solid waste (MSW) generation is influenced by economic conditions, living standards, urbanization, and population (Kawai and Tasaki, 2016)[[7]](#footnote-7). In 2012, Hoornweg and Bhada-Tata co-authored a World Bank report, *What a Waste* (Hoornweg and Bhada-Tata, 2012)*[[8]](#footnote-8)*. Waste generation estimations in the report are calculated according to urban population forecasts (population in cities), waste composition rates and country income level. These three variables are major variables to consider when making future waste projections.

Estimations from the World Bank report included a rise in global solid-waste generation from more than 3.5 million tons per day in 2010 to more than 6 million tons per day in 2025. That means that currently 1.3 billion metric tons of municipal solid waste (MSW) are generated annually in the world, and by 2025 the numbers will rise to about 2.2 billion tons annually. These values are estimated according to urban populations and per capita GDP estimations forecasted for several decades in the study of Hoornweg et al. (Hoornweg et al., 2013).

Figure 3 shows waste generation in the past and projections for the future in the world and its regions (Hoornweg et al., 2013).

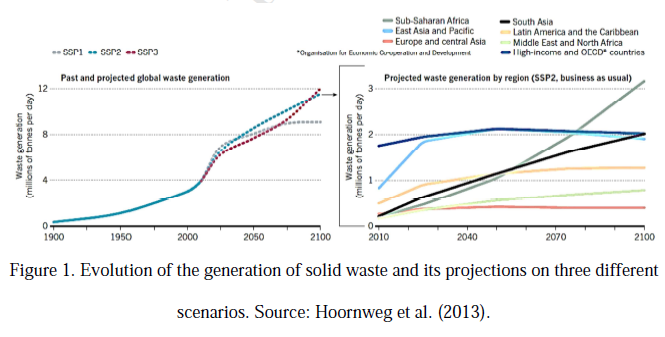


Figure 3: Projections of solid waste generation according to three different scenarios (Hoornweg et al., 2013)

In the first scenario (SSP1) for 2100, 90% of the 7 billion of the world population live in cities, and development goals are achieved with reduced consumption of fossil fuels and environmentally aware citizens. In the second scenario (SSP2), world population is 9.5 billion people and 80% urbanization (intermediate scenario). In SSP3 scenario, there are 13.5 billion people and 70% live in cities. There is extreme poverty and moderate wealth. Many countries have high rates of population growth such as in Africa and Asia (Hoornweg et al., 2013)[[9]](#footnote-9). In Latin America, for intermediate scenario, the trend is that waste generation will grow strongly until 2025, and then grow less until 2070 and then stabilizes. SSP2 scenario is chosen as the default scenario in this study.

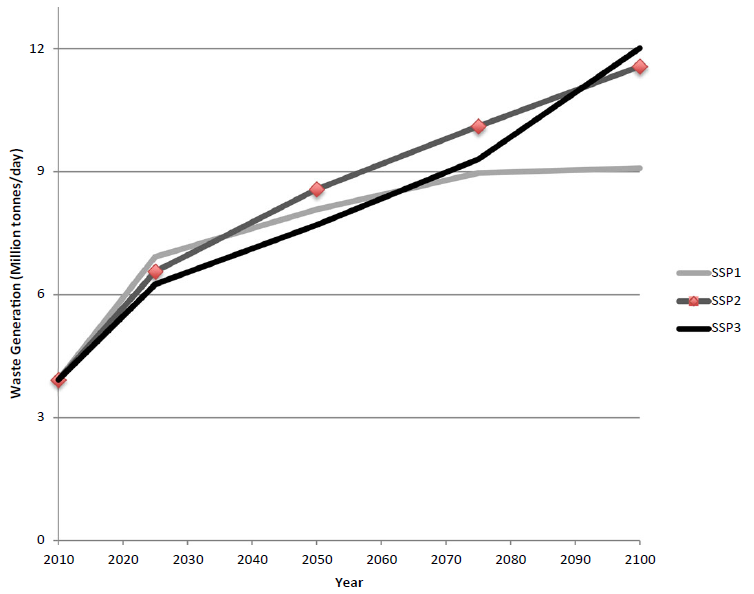


Figure 4: Projections of global solid waste according to three different scenarios (Hoornweg et al., 2014)[[10]](#footnote-10)

According to Figure 2, waste generation in OECD countries will peak by 2050. Waste generation in Asia and Pacific countries tends to rise until 2075. The cities in sub-Saharan Africa will grow fast and waste their citizens generate will continue to rise. According to Dyson and Chang, urbanization of Africa will be the main determinant of intensity of global peak waste (Dyson and Chang 2005)[[11]](#footnote-11).

Low and middle-income countries have a higher percentage of organic matter in their solid waste (up to 88%) versus high income countries (<56%). However these developed countries have a higher amount of organic waste destined to composting (Hoornweg and Bhada-Tata, 2012). Developing countries such as China, Brazil and Mexico have the greatest share of organic matter in their waste. Developed and richer countries have less organic matter and more recycled materials. Recycled materials are usually glass, plastics, paper, steel and aluminum.

Additional data on waste generation, management and composition in OECD countries can be found in official OECD databases (OECD Environment Statistics 2016)[[12]](#footnote-12). Karak et al. used data from World Bank report (Hoornweg and Bhada-Tata, 2012) to estimate waste generation and composition values per capita in order to lower the uncertainty that origins from making forecasts depending on estimation of population growth (Karak et al., 2012)[[13]](#footnote-13).

## State of Household and Commercial Recycling

Waste may be recycled by collection from mixed waste streams, and separation of different types of waste after. Alternatively, different types of waste may be collected separately by using special garbage recycling bins and collection vehicles.

Table 2: Analysis of municipal waste, household rubbish, and bio-waste

|  |  |
| --- | --- |
| Municipal Waste Stream | Environmental risk (Business-As-Usual) |
| Biodegradable waste (food leftovers) | - Methane in landfills (not included in the analysis) |
| Packaging waste | * Most of consumer products come in packaging which uses (paper, cardboard, wood, plastic, metal, and glass) that consumes materials and energy in production and compromises increasing amounts of metals and non-degradable plastics emitting toxic substances during incineration (energy recovery) if not recycled. |
| Hazardous household waste (HHW) | * Batteries, garden chemicals, oils, paints, solvents, and out-of-date medicines which are typically present in quite small quantities that may cause serious environmental impacts (groundwater and soil pollution), or fires and explosions. |

In its Waste Directive 2008/98/EC[[14]](#footnote-14), the European Commission applies the waste hierarchy in which recycling is a stand-alone waste management practice. EU promotes optimal recycling, which includes separate collections of waste where technically, environmentally and economically practicable and appropriate to meet the necessary quality standards for the relevant recycling sectors. Paper, metal, plastic and glass are among these relevant sectors.

Paper is not included in the recycling solution, because a solution Recycled Paper is already been analyzed in a separate study.

### Waste Collection, Transport and Separation

Waste generated by households, public institutions and commercial and industrial enterprises and which is handled by municipalities is collected, separated, and transported to recycling centers. Waste separation or sorting may also take place in households, where people can use different bins to dispose of their waste. Sorted waste may be collected by curbside collection or at centralized collection points. If waste is not sorted at the source, it is transported to centralized material recovery facilities (MRF) to separate wastes for recycling and waste for other treatment. Sorting may be manual or automated, sorting includes breaking waste and discarded products (i.e., with a shredder) and compacting identical types of waste for shipment to facilities which produce materials.

### Recycling Metals

“Virgin” or “raw” materials, such as trees or ore, are harvested directly from the earth, then transported and processed. These activities use a large amount of energy, and the burning of fossil fuels to supply this energy results in greenhouse gas emissions. Recycling generally uses less energy than extracting and processing raw materials, because making new products from materials that have already been used (recycled materials) can save energy and reduce greenhouse gas emissions. When a product is made with less material, or materials made with recycled content, less energy is needed to extract, transport, and process raw materials.

Resource snapshots (estimations of raw materials use and consumption) on copper, coal, aluminum, gold, phosphorous, lead, water, silver and diamonds can be found at WRforum website (WRForum 2016a)[[15]](#footnote-15), as well as scenarios for future resource extraction (WRForum 2016b)[[16]](#footnote-16)[.](http://www.wrforum.org/publications-2/publications/)

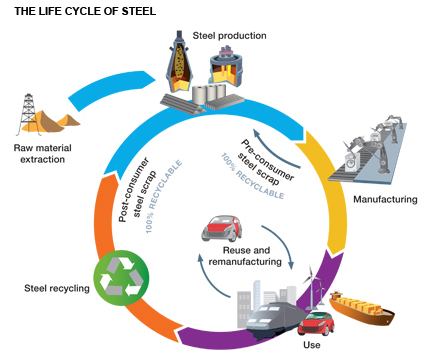


Figure 5: The life cycle of steel (WorldSteel)[[17]](#footnote-17)

, and naturally contribute to resource conservation through their lightweight potential, durability and recyclability (World Steel 2016)[[18]](#footnote-18). Due to its magnetic properties, steel is easy to separate from waste streams, enabling high recovery rates and avoiding landfills. Recycled steel is a key input needed for all steelmaking. There are over 650 Mt recycled annually, including pre- and post-consumer scrap (World Steel 2016). About 83% of post-consumer steel is recovered for recycling (World Steel 2016). By sector, global steel recovery rates are estimated at 85% for construction, 85% for automotive (reaching close to 100% in the US), 90% for machinery, and 50% for electrical and domestic appliances. Recycling steel accounts for significant energy and raw material savings: over 1,400 kg of iron ore, 740 kg of coal, and 120 kg of limestone are saved for every 1,000 kg of steel scrap made into new steel (World Steel 2016).

Other metals that also have high recycling rates typically have streamlined uses in which they are not in highly-populated goods, making separation easier. Lead, for example, is almost exclusively used in lead-acid batteries now, as many other uses have been banned due to health concerns, and therefore has a recycling rate close to 90%. Aluminum, also, which has primary uses like cans, wiring, and plates that are high purity, has a high recycling rate, over 60%. Metals such as copper, magnesium, titanium, or REEs that are used in high complexity electronics or alloys tend to have lower recovery rates.

### Recycling Plastics

Some types of plastics are recycled more often than others. PET, HDPE, LDPE, PP, PS, and PVCs are more economically feasible to recycle. These types of plastics, and thermoplastics in general can be melted and reused or broken back to feedstock state. Difficulties with sorting and separating different types of plastic are the main reasons that plastics is not more widely recycled. Usually, the type of plastic is not marked or identifiable on the plastic items themselves, so it is difficult to know the type of plastic to be able to sort it correctly. Thermoset plastics degrade in quality when reused.

### E-waste Recycling

Waste from electrical and electronic equipment, or e-waste, can be recycled, but mechanical shredding and separation is expensive and low in efficiency, and often poses more significant environmental risks than other types of waste, especially when dealing with older products. Thus, e-waste is often exported to developing countries where salaries and occupational health and safety standards are lower. Electrical and electronic equipment contains plastics, gold, copper and other metals, heavy metals (in batteries), and halogenated products (e.g. flame retardants). E-waste can include hazardous or nonhazardous substances. Batteries contain dangerous elements such as lead, mercury, and cadmium which can explode and leak to the environment.

The composition of WEEE/e-waste is very diverse, as electrical and electronic equipment encompasses such a broad range of categories (Baldé et al., 2015)[[19]](#footnote-19). In general, it contains a combination of metals, plastics, chemicals, glass and other substances. Among the substances of interest are a very wide range of metals including rare earth metals like lanthanum, cerium, praseodymium, neodymium, gadolinium and dysprosium; precious metals such as gold, silver and palladium; or other metals such as copper, aluminum or iron with a high intrinsic price value. However, even though ‘critical materials’ are scarce, they have recycling rates lower than 1%. According to Global e-waste monitor report, the total amount e-waste generated in 2014 was 41.8 million metric tons (Mt), and it is forecasted to increase to 50 Mt of e-waste in 2018 (Baldé et al., 2015). Only 6.5 Mt of the 41.8 Mt of e-waste are recycled with the highest standards, since that amount of e-waste was reported as formally treated by national take-back systems (Baldé et al., 2015). Annual growth rate is estimated at 4% to 5%.

## Adoption Path

As recycling of waste includes several processes it is highly dependent on the adoption of those processes in a region, town or country level. For example, collection of waste is higher in high-income countries than in low-income countries. Landfill and other waste treatment options are preferable options for municipalities because recycling demands careful sorting of collected waste to different waste types, e.g. metals, plastics, glass, rubber, wood, textiles, e-waste and other. Current adoption of recycling according to the Total Addressable Market of Recyclable Waste (metals, plastic, glass and other) is estimated according to 2010 regional data on waste recycled from What A Waste report (World Bank 2012).



Figure 6: Greenwaste Recycling, San Jose, CA, used in Gershman, Brickner & Bratton[[20]](#footnote-20)

## Advantages and disadvantages of Municipal Solid Waste Recycling

Waste management is related to managing solid, liquid and other types of waste generated, and aims at reducing negative impacts on human health and the environment. Major environmental impacts caused by waste are significant losses of materials that turn out in the waste stream as mixed solid waste. This causes pollution due to emissions into water bodies, sediments, oil, and air, greenhouse gas emissions from treatment or landfills (methane), release of acid gases and other hazardous substances as dioxins due to poor or incomplete burning of waste.

Preference of different waste management strategies is shown in Figure 2. Figure 2 points out that reuse and dematerialization result in greater GHG reductions, and recycling is preferable to Waste to Energy.

Waste to Energy is a viable alternative to recycling. Energy recovery from waste is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of processes. Converting non-recyclable waste materials into electricity and heat—generally through combustion or landfill gas recovery—which reduces carbon emissions by avoiding the need for energy from fossil sources. In addition, these methods reduce generation of methane, a potent greenhouse gas, from landfills (EPA 2016).

Reuse, or using a product more than once, prevents the need to create the product from scratch, which saves resources and energy while also preventing pollution.

### Advantages

Recycling has great potential for reducing GHG emissions and saving energy. Manufacturing goods from recycled materials typically requires less energy than producing goods from virgin materials (EPA 2016). The major advantage of recycling is that recovered materials can be used instead of primary materials (materials produced from virgin sources). Secondary recovered materials save energy and fossil fuels needed in conventional virgin materials production.

Factors influencing the benefits of recycling:

1. Integrating organic and non-organic waste recycling

The results show that recycling and composting can minimize the emission of greenhouse gases, reducing carbon dioxide and carbon equivalents, and promote energy savings[[21]](#footnote-21). Integrated management can reduce 78.8% of carbon dioxide and save 490.9% energy.

1. Informal waste pickers

The key advantages of recycling and recovery are reduced quantities of disposed waste and the return of materials to the economy. In many developing countries, informal waste pickers at collection points and disposal sites recover a significant portion of discards. In China, for example, about 20% of discards are recovered for recycling, largely attributable to informal waste picking (Hoornweg et al 2005). (What a waste, p. 28)

### Disadvantages

Waste collected needs to be transported to a waste sorting facility, and then sorted materials need to be transported to recycling centers or material recovery facilities. Each stage of waste recycling and waste management needed for the waste to get from households and institutions to recycling facilities require some form of transportation. Transportation by plane, truck, or rail all require the use of fossil fuels for energy, which significantly contribute to global warming and GHG emisisons.

Cost of activities and processes that enable recycling, as well as investment which is needed in technology and waste management are the main barriers to greater adoption of this solution globally.

# Methodology

## Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment) is what constituted the results.

## Data Sources

Waste considered in this study is post-consumer waste measured at waste collection centers. Pre-consumer waste is found in far smaller amount of only 10% of total post-consumer waste generated by households, residential, commercial and institutional subjects. Pre-consumer waste is also almost 100% recyclable on-site. The amount of pre-consumer waste that is lost from the material cycle is hence negligible (EU Joint Center 2002).

Data used to develop the Recycling TAM is based on the Recyclable fraction of waste from What a Waste 2.0, and then applied to the Integrated Waste TAM estimate of total MSW. World amounts of recyclable waste are calculated as a sum of recyclable waste in regions.

## Total Addressable Market

The total addressable market for this model is determined in the Waste TAM model. It is based on What a Waste and What a Waste 2.0 approximations of the global recyclable fraction of MSW in 2010, 2016, and 2025, where recyclable fraction encompasses glass, plastic, metal, and other waste. These percentages were extrapolated to determine a trend for the entire time period of 2015-2050, and applied to the total global Waste TAM. This recyclable fraction of global MSW is the Reference TAM.

Post-integration, adoption of bioplastics in the plastics market has a significant influence on the TAM. The biodegradable fraction of bioplastics adoption is removed from the TAM and allocated to the organic (composting) TAM. For this reason, the post-integration TAM for PDS1 is larger than PDS2, which is in turn larger than PDS3, since they include incrementally more bioplastics adoption.

## Adoption Scenarios

There are three PDS adoption scenarios developed and all are based on achieving a certain recycling rate (% recycled MSW of total recyclable MSW (less paper).

### Reference Case / Current Adoption

The baseline scenario assumes that no new and innovative policy measures, investment or initiatives are introduced to further prevent the generation of waste or to further divert waste from landfill.

Current adoption rate of household and commercial recycling globally is estimated according to What a Waste 2.0 values for 2016, which shows that a majority of waste generated is landfilled (37% landfilled, 11% incinerated, 33% open dumping, and only 13.5% recycling). Of the recyclable fraction of waste, approximately 38% was recycled.

### Project Drawdown Scenarios

There are several factors that arrest the development and implementation of recycling programs such as government, educational, financial, administrative, and other factors (Troschinetz and Mihelcic, 2009). However, it is possible to implement successful programs that can achieve high levels of recycling as in Graz, Austria, where about 69% of recylable waste was recycled through a municipal program in 2004 and only 14% was disposed in a landfill (Moczygemba and Smaka-Kincl, 2007). This is the reason why EU set a 70% recycling target for 2020, and this recycling target rate is most plausible as a recycling target for OECD countries in 2050.

The PDS1 scenario is based on OECD countries meeting the EU Target of 70% recycling by 2050, and all other regions growing to current US adoption levels (57%). PDS2 is again based on OECD countries meeting the EU 70% target, and other regions meeting current adoption in Germany and Austria (approximately 62%). The PDS3 scenario, the most aggressive, finds OECD recycling 80% of waste by 2050, and other regions meeting the EU goal of 70% by 2050.

These scenarios are considered optimistic, yet plausible. Optimistic, because they show growing adoption of recycling to the level of the highest level of current adoption today in the affluent world. Plausible, because the regions where that high level of adoption exists today demonstrate that under the right conditions, policies and investments such an adoption is not outside of what is considered possible.

## Inputs

### Climate Inputs

GHG emissions from recycling processes are direct emissions, and GHG emissions avoided due to use of recycled materials instead of virgin materials are avoided emissions (Bakas et al., 2011)[[22]](#footnote-22). Direct emissions are caused by all activities directly involved energy-related GHG emissions from collection, and transport of waste, and emissions from recycling plants. Avoided emissions are the GHG emissions from activities such as energy production from fossil fuels and production of primary materials that would be generated if there was no (0%) energy recovery from waste incineration and from landfill methane recovery, and no (0%) material recuperation from waste recycling.

Direct Emissions (conventional):

* Emissions from landfilling
* Emissions from open dumping
* Emissions from MSW collection & transport
* Emissions from virgin material production

Direct Emissions (solution):

* Emissions from MSW collection & transport
* Emissions from waste sorting and recycling in Biological-Mechanical treatment facilities or Material recovery facilities
* Emissions from material production from recycled feedstocks

Indirect emissions are also considered, and include emissions savings from manufacturing goods from recycled feedstocks as opposed to virgin materials.

All climate inputs in the model are converted to be expressed per million metric ton of MSW.

### Financial Inputs

Costs associated with uncollected municipal solid waste are not included in this study. The main costs associated to the solution in this study are first or capital costs and operational costs. In case of the conventional solution first costs can be associated to installing landfills, costs of equipment and permits needed for opening a landfill. First costs of recycling solution can be associated to building and installing material recovery facilities (MRF) or mechanical-biological treatment (MBT) facilities. In these facilities, waste is sorted and capital costs of such facilities are costs of equipment, construction of the building, buying land on which facilities are build and others. MBT and MRF facilities have a 10-20 years life span.

The main components of operation costs are costs of labor, fuel, energy, maintenance and repair, emission control and monitoring, revenue collection, public communication and management and administration (UNEP global monitor 2015). Revenues obtained for recovered materials is typically lower than separation/reprocessing costs, which can be, in turn, higher than the cost of virgin materials) (Bogner et al., 2007)[[23]](#footnote-23). In the literature references, revenues are already included in operating costs.

Costs (conventional):

* Cost of collection of municipal solid waste (operational transport costs, e.g. fuel, cost of labor)
* First cost of installing new landfills
* Operating costs of maintaining landfills (taxes, labor costs)

Costs (solution):

* Cost of collection of municipal solid waste (operational transport costs, e.g. fuel, cost of labor)
* First cost of installing new waste sorting facilities
* Operating costs of waste sorting facilities (labor, electricity, taxes - these costs are expressed as net of any revenues from sale of recovered materials)

## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at [www.drawdown.org](http://www.drawdown.org). Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

1. Quantity and type of municipal solid waste disposed and waste management practices in regions and countries reported in different studies mentioned in this work corresponds to municipal solid waste generated.

* It is been considered that the amount of MSW disposal do not necessarily correspond to those of MSW generation, especially in developing countries (Kawai and Tasaki, 2016). Data acquisition on MSW generated is especially challenging to collect and analyze, since it is influenced by economic conditions, living standards, urbanization and population, and infrastructure for data retrieval on waste generated, disposed, type of waste and waste composition is very unevenly distributed across the globe.
* In the literature review of current and future waste generation, these limitations are acknowledged, so municipal solid waste disposed is used as a proxy of municipal solid waste generated. The same assumption is made by authors when making estimations of future waste trends.

1. Default scenario of future global solid waste generation is the intermediate scenario SSP2 (Hoornweg et al., 2014) with total population estimated at 9.5 billion people and 80% urbanization in 2025.

* Projections of solid waste generated in the future are dependable on several variables such as projected population, urban population and density of urban places and cities, as well as changes in GDP and country income level. This scenario is chosen because it is an intermediate scenario concerning poverty and wealth, and percentage of people living in cities. Total world population in 2100 is estimated to 9.5 billion people, which is very close to 10 billion total population in 2100 forecasted by the MESSAGE model.

**Assumption 3:** The solution includes both household and commercial recycling. The approach taken is that waste collected by municipalities include also waste generated by companies, public institutions and industry which do not exclusively implement product take-back practices.

**Assumption 4:** Energy used in the production of goods from virgin material feedstocks and recycled material feedstocks comes from grid electricity and emissions from that energy used are grid emissions factors.

## Limitations/Further Development

The state of currently operating landfills and material recovery facilities could not be determined within the scope of this study. Because of the limitations to establish how much waste can be landfilled in currently operating landfills and how much of the capacity of currently operating material recovery facilities is not exploited to its full potential, first costs of such facilities are calculated for installing completely new facilities.

Similar limitations of the study have been identified with establishing first costs of introducing new solid waste collection systems by municipalities, and the unused capacity of existing ones.

Due to scope of the study recycling some materials such as bio-plastics, concrete, ceramics, rubber and e-waste have not been studied in depth because it would require a detailed prognostication of those materials and waste for the period included in the study. Because of lack of data on current and future ratios of these materials and wastes in global and regional waste, these materials and waste were not studied in detail, but were included under type or waste ‘other’. Sorting and recycling e-waste requires additional investments and due to the complexity of these processes and business practices, e-waste recycling has not been analyzed in full depth.

Additionally, the fraction of MSW that is recyclable may be more dynamic then the model represents. The model uses prognostications from What a Waste (World Bank 2012) to forecast a dynamic shifting fraction of recyclable material of MSW per region. Additional sources of estimating future fraction were not available.

# Results

## Adoption

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios.

Table . World Adoption of the Solution

| **Solution** | **Units** | **Base Year (2018)** | **World Adoption by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Drawdown** | **Optimum** |
| Solution Name | *Million Metric t of Recyclable MSW* | 292.61 | 620.79 | 650.22 | 476.21 |
| *(% market)* | 41.2% | 66.8% | 88.6% | 100.0% |

A screenshot of a cell phone

Description automatically generated

## Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the glossary (Section 6).

Table . Climate Impacts

| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Emissions Reduction in 2030** | **Emissions Reduction in 2050** |
| --- | --- | --- | --- | --- |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/year)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.62 | 11.09 | 0.27 | 0.62 |
| ***Drawdown*** | 0.68 | 12.08 | 0.29 | 0.68 |
| ***Optimum*** | 0.77 | 13.59 | 0.36 | 0.31 |



The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table . Impacts on Atmospheric Concentrations of CO2-eq

| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| --- | --- | --- |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 0.919 | 0.047 |
| **Drawdown** | 1.002 | 0.052 |
| **Optimum** | 1.102 | 0.011 |

## Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Table . Financial Impacts

| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Cost Savings** | **Lifetime Operating Cost Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| --- | --- | --- | --- | --- | --- |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | 153.29 | 6.91 | -30.97 | -46.31 | -8.01 |
| **Drawdown** | 162.56 | 7.46 | -33.75 | -50.47 | -8.58 |
| **Optimum** | 174.80 | 5.26 | -37.99 | -39.61 | -8.01 |

# Discussion

Solid waste, on average, represents less than 5% of a product’s overall environmental impact (Hoornweg and Thomas 1991). Monitoring worldwide solid waste volumes is a good substitute for monitoring overall global impact resulting from material-based consumption (Hoornweg et al., 2015)[[24]](#footnote-24).

In the context of household commercial recycling, the following technologies will have an important impact on the adoption of this solution worldwide (Phylipsen et al, 2002):

* In disassembly, recovery and recycling:
* waste-identification systems;
* waste-separation systems;
* recycling and recovery of rare metals from applications such as mobile phones, PV systems, etc.

Development in the technologies of material recycling, product recycling and end-of-pipe technologies such as waste identification and sorting technologies, waste disassembly and shredding technologies and material recovery technologies will have positive impacts on lowering first costs and operating costs of recycling.

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# Glossary

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

**Approximate PPM Equivalent** – the reduction in atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net** **Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV’s in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings**–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

**Lifetime Cashflow NPV**-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Drawdown Scenario** – this is the high growth scenario for adoption of the solution

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

**Regrets solution** has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** are considered till better technologies and less impactful are more cost effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours

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