Waste-to-Value

Research Paper Q1 2020

VERTO™

Verto Management, LLC

Verto Management, LLC ("Verto") was established in 2018 and is dedicated to originating and investing in Waste-to-Value ("WtV") opportunities. The firm is headquartered in Boston, MA, with additional offices in Washington, D.C. and Vancouver, B.C.

With over 100+ years of combined experience, the Verto team has developed, structured, owned, operated, and managed WtV, infrastructure and natural resource assets across the globe. By leveraging its specialist industry knowledge, Verto originates and prepares high-impact WtV platform investment opportunities for sophisticated capital.

Verto partners with impact projects and private companies that support a circular economy by converting waste into sustainable value through reuse, repurpose, or recycling. As an UN-PRI signatory, Verto is committed to the integration of ESG principles into opportunity selection, investment evaluation and management practices, following the UN Sustainable Development Goals.

This report provides a current overview of the growing global waste market and analyzes specific key markets in North America and OECD Europe where Verto targets investment opportunities in waste-to-energy, fuels and materials. Given the size and scale of the waste market, Verto's business model is focused on unlocking investment potential by enabling impact investments in Waste-to-Value.

Contents

Executive Summary

The world produces a colossal amount of waste, and it is forecasted to grow significantly over the coming years. World Bank data released in 2018 estimated that Municipal Solid Waste (MSW) generated by households, institutions and commerce across the world totaled approximately 2.0 billion tons in 2016. It estimates this figure to grow by 69% over the next 30 years, reaching 3.4 billion tons by 2050[1].

1. Source: United Nations Environmental [Program: Global Waste Management Outlook]

With the addition of commercial and industrial waste (including agricultural, construction and demolition wastes), total global waste from all activities is estimated to be around 7-10 billion tonnes per annum.

At a global level, it is approximated that only 13.5% of today's MSW is recycled and 5.5% is composted. Between 33% and 40% of generated waste is improperly managed, instead being dumped or openly burned.

Everyone produces waste of some kind. The World Bank characterizes waste as a pressing global crisis. In both the developed and developing worlds, there are significant challenges facing countries and communities as a result of an ever-increasing amount of waste being produced by our consumer-driven society.

When managed poorly, waste presents significant challenges that affect health, productivity and cleanliness in communities. Poorly managed waste contaminates land, air and water sources, pollutes the world's oceans, clogs drains, releases greenhouse gases into the atmosphere and can cause flooding and transmission of disease.

According to the United Nations, good decision making about how we manage the waste created by the people of the planet is one of the most important contributions humanity can make to reducing its impact on the natural world. Environmentally sound waste management is one of the key elements for sustainable development.

When managed effectively, however, waste can provide a highly valuable opportunity. Virtually all types of waste can be converted into a lucrative resource, whether it be solid, liquid or gas fuel, energy in the form of electricity or heat, or a range of materials and chemicals that can be repurposed into new products. The waste-to-value opportunity, which encompasses a move to a 'circular economy' and away from the use-once-and-throw-away 'linear economy,' is significant in size and scope.

Section 1

Overview of the Global Waste Market Opportunity

Where in the world is all the rubbish?

The following graphic provides an overview of waste generated by continental regions of the world in 2016, in addition to forecasts for 2030 and 2050. Figures are in millions of MT.

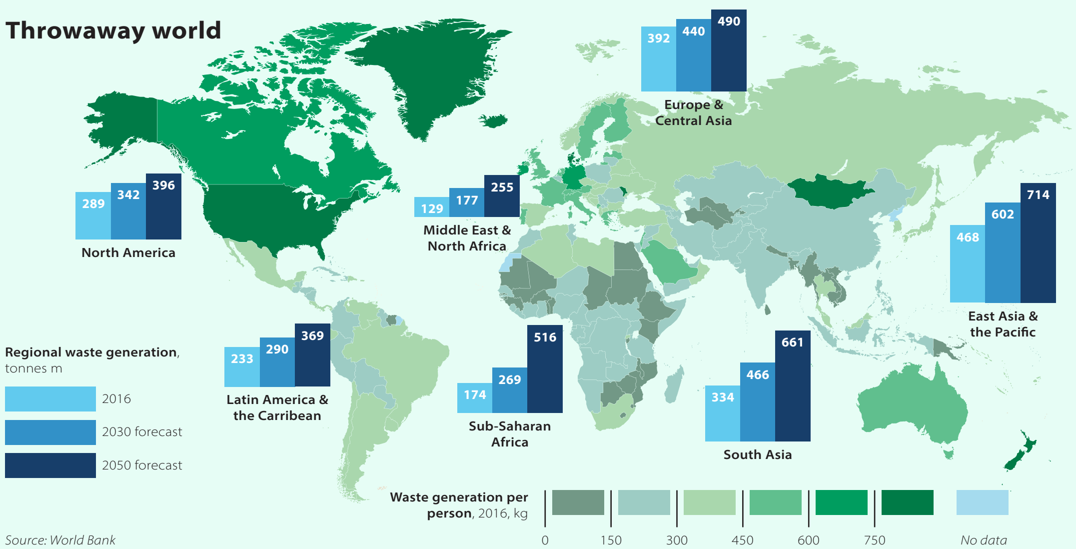
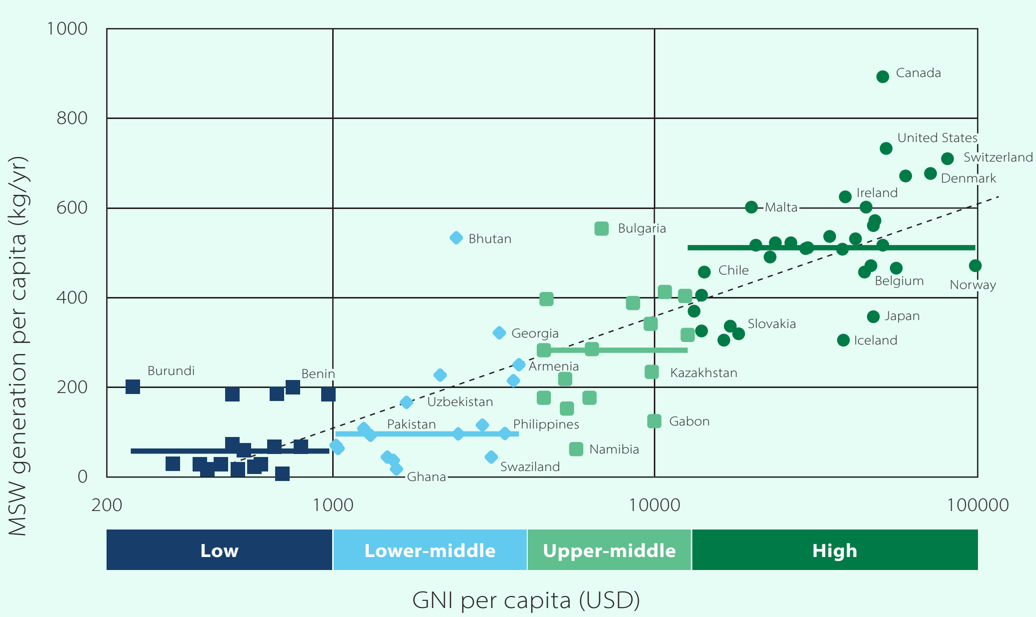


Fig 1: "Global waste generation, by continental region (in millions of MT)"

Although waste generation rates vary widely within and between countries, MSW generation per capita is strongly correlated to national income.



United Nations Environmental Program Global Waste Management Outlook 2015

Fig 2: *"Waste generation (in kg/per capita/year) versus income level, by country"*

In high-income countries, per-capita MSW generation rates are now beginning to stabilize and even show a slight decrease, which may indicate the beginning of waste growth 'decoupling' from economic growth.

In low and middle-income countries, however, as economies continue to rapidly develop and grow, per-capita waste generation rates can be expected to grow steadily in the future.

Waste generation is growing rapidly in all but the high-income regions of the world as populations rise, migrations to cities continue, and economies develop. In 2010, high-income countries accounted for around half of all waste generation. This is forecasted to change quickly with Asia overtaking these countries in terms of MSW generation by 2030, and Africa potentially over taking both in the latter part of the 21st century.

Key drivers of the global increase in waste generation

Principal drivers of the significant increase in waste generation are population growth, urbanization and increasing incomes.

2. History Database of the Global Environment (HYDE), UN World Population Prospects

3. Ourworldindata.org, UN Population Division

Increasing population

The current global population (in 2019) stands at 7.7 billion. This is projected to grow to 9.7 billion in 2050. It is estimated that in the next 13-15 years, a net one billion additional people will be added to the world's population, and the next net one billion in 14-16 years[2]. Total population by 2100 is estimated to be 10.9 billion[3]. Most of the gain in global population - and its consequential increase in waste - is projected to be in South Asia, East Asia and sub-Saharan Africa.

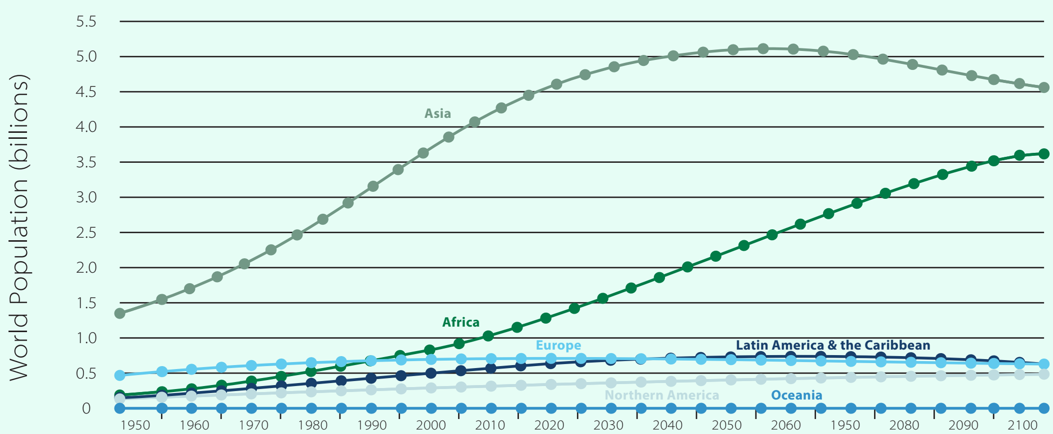


Fig 3: *"Estimated and projected world population, by region 1950-2100"*

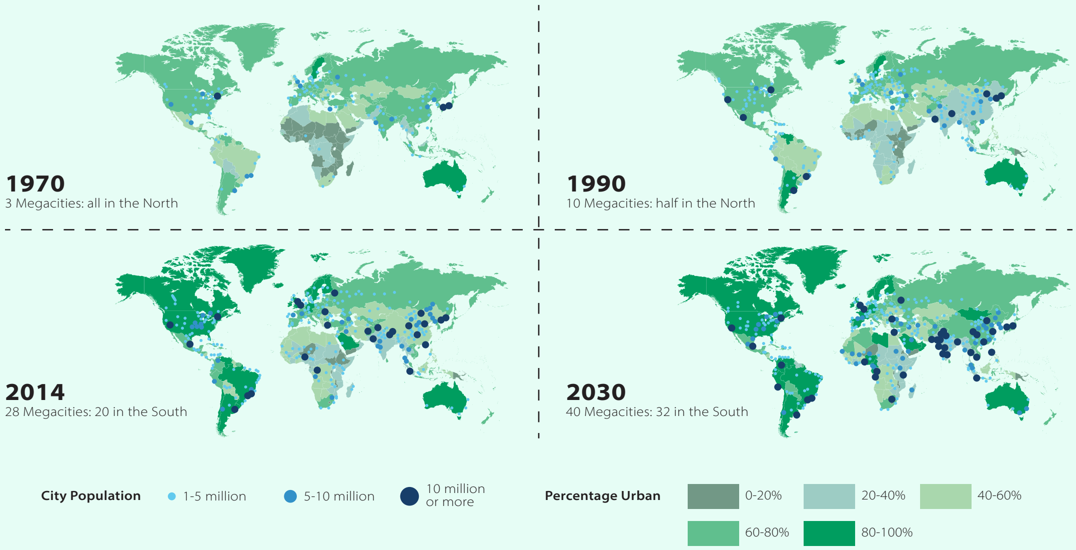
. United Nations Environmental Program Global Waste Management Outlook 2015

Increasing urbanization

Waste generation is significantly greater in urban areas than in rural ones. Since the 1950s, we have seen a significant increase in urbanization around the world. Global urban population was 30% in 1950. In 2019, urbanization has reached 56%. This is forecasted to further rise to 60% by 2030 and to 68% by 2050[4].

As the urban population grows, we will witness an increased number of consumers purchasing supermarket and consumer goods, which generates a significant amount of associated packaging and other waste streams, in comparison to those produced by rural populations.

4. Ourworldindata.org, UN Population Prospects 2018



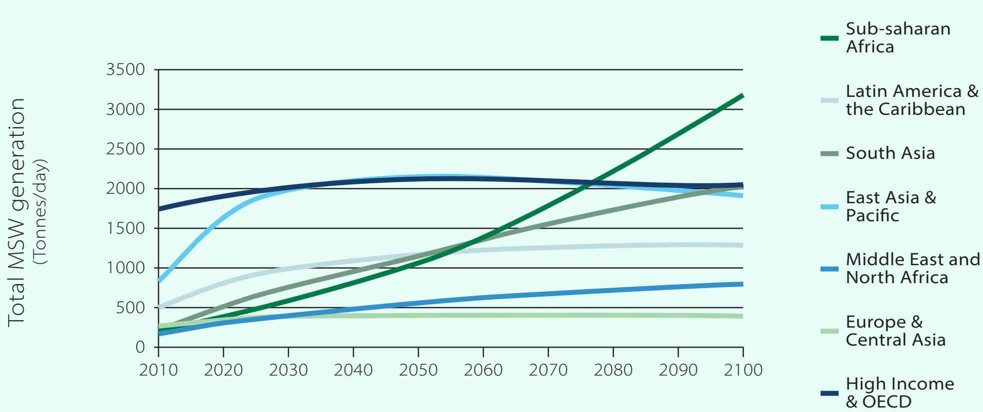
Source: United Nations Environmental [Program: Global Waste Management Outlook]

Fig 4: "Percentage of urban population and locations of large cities 1970 – 2030"

The graphic above shows the percentage of people living in urban areas, delineated by the country and location of cities in size ranges of 1-5 million, 5-10 million and more than 10 million. Whereas there were only 3 mega-cities with a population of more than 10 million in 1970, by 2030 it is forecasted there will be 40 mega cities of this size, with around half of these in South Asia and South East Asia.

In 2014, urban populations were already at or approaching 80% in much of North and South America, Europe, Japan and Australia. The trend of migration to cities still has a long way to run, particularly sub-Saharan Africa. This coincides with regions where total population is expected to continue the strongest growth.

The following chart shows projections for MSW generation by world region from 2010 - 2100, in MT per day.



[United Nations Environmental Program Global Waste Management Outlook 2015]

Fig 5: "Total MSW generation by region (in MT per day)"

The chart shows that in high income and OECD countries, waste generation is estimated to rise slowly, stabilize and then decline over the course of this century. As a percentage of the world's total waste, it is declining sharply over the period. MSW generation in East Asia and the Pacific is forecasted to rise very sharply in the period to 2030, before stabilizing. In South Asia, a relatively strong linear growth in MSW is estimated to 2100. Sub-Saharan Africa is forecasted to see accelerating growth to 2050 and may become the dominant region in waste generation thereafter.

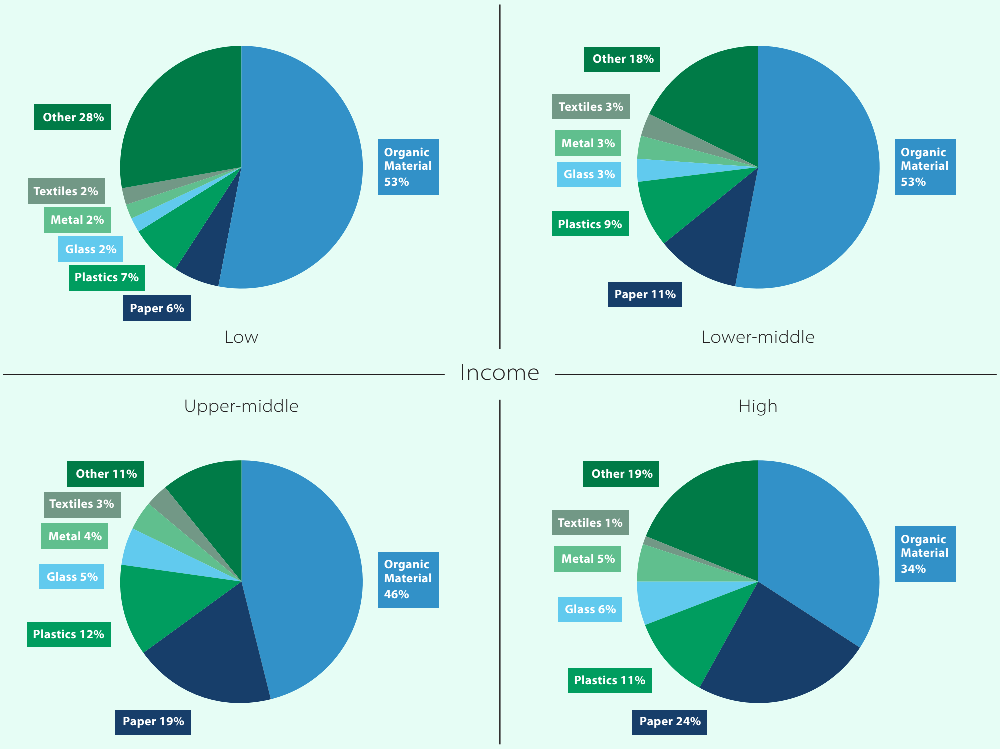
Increasing incomes

There is a significant correlation between income and waste generation. As people become wealthier and gain a higher level of disposable income, they consume more. As a result, they produce more waste. In general, countries with a high GDP per capita produce a higher waste per person than low-income countries. According to World Bank data, India, for example, with a GDP per capita of US$1,717 in 2016, generated an average of 180kg waste/person/year. The US, by comparison, had a GDP per capita of US$57,588 in 2016, and generated an average of approximately 740kg/person/year.

In some high-income countries, notably several European countries and developed Asian countries like South Korea, Taiwan and Japan, MSW generation rates are starting to stabilize, indicating the beginning of a waste growth 'decoupling' from economic growth. This is reflective of campaigns to actively promote awareness of the importance of sustainable living, universal (100%) collection rates, investment in recycling and modern waste management infrastructure.

What is in all the waste (MSW)?

The following pie charts show the composition of MSW by country income levels.



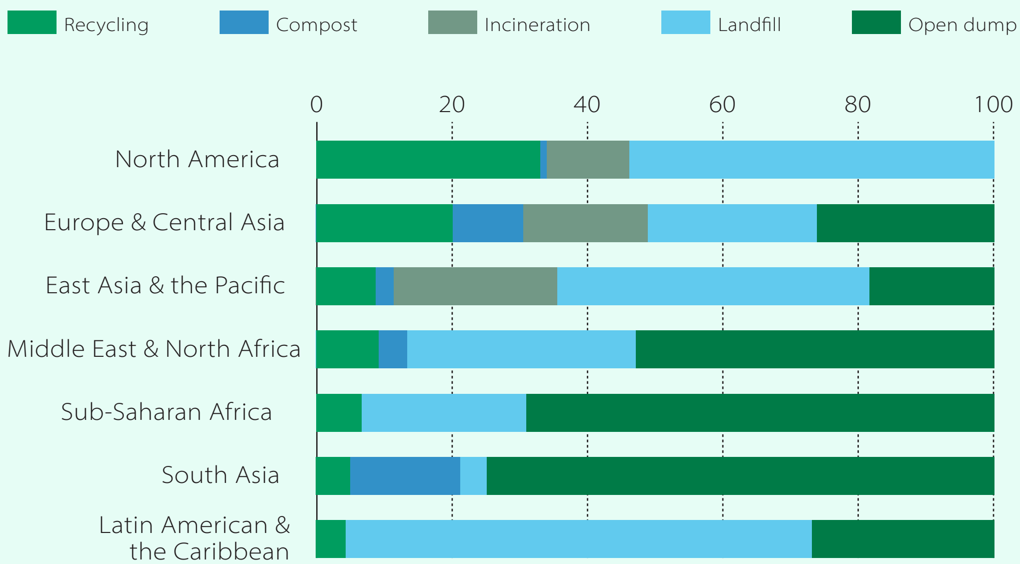
Source: United Nations Environmental [Program: Global Waste Management Outlook]

Fig 6: "Variation in MSW composition grouped by country income levels"

In terms of waste composition, one notable difference between high and low-income countries is the amount of organic fraction (food and garden waste). For low-income countries, the organic material averages 53%, compared to 34% in high-income countries.

The percentage of paper waste is another area that reveals a stark difference, with an average of 24% in high-income countries and 6% in low-income countries. In high-income countries, the proportion of waste generated from plastics, glass and metals are all higher at 11%, 6% and 5%, respectively. This compares with 7%, 2%, and 2% in low-income countries, respectively.

The graphic below shows how the world's waste is treated by region.



. World Bank data, The Economist Speaicl Report "A Load of Rubbish", September 2018

Fig 7: *"Global waste disposal methods for MSW, 2016, (in %)"*

Highly notable is the proportion of waste that is disposed of in open dumps in lower-income parts of the world. This is particularly prevalent in South Asia, the Middle East, North Africa and sub-Saharan Africa, and can have significantly adverse environmental and health impacts (see section below).

Landfilling is the most common disposal method in both North and South America. While Europe and Central Asia show a mixed picture, the European Union is one of the most progressive parts of the world with respect to waste treatment, following the introduction of The Waste Hierarchy which promotes reuse, recycling and composting of waste (including anaerobic digestion) in the first instance. For waste where this is not possible, it next encourages energy recovery from incineration, and discourages landfilling, except as a last resort. Open dumping in the EU is prohibited.

In 2017, 46% of MSW in the EU was recycled and composted, 28% was incinerated with waste recovery, 23% was landfilled, and 3% used other treatment methods.

What big problems are caused by waste?

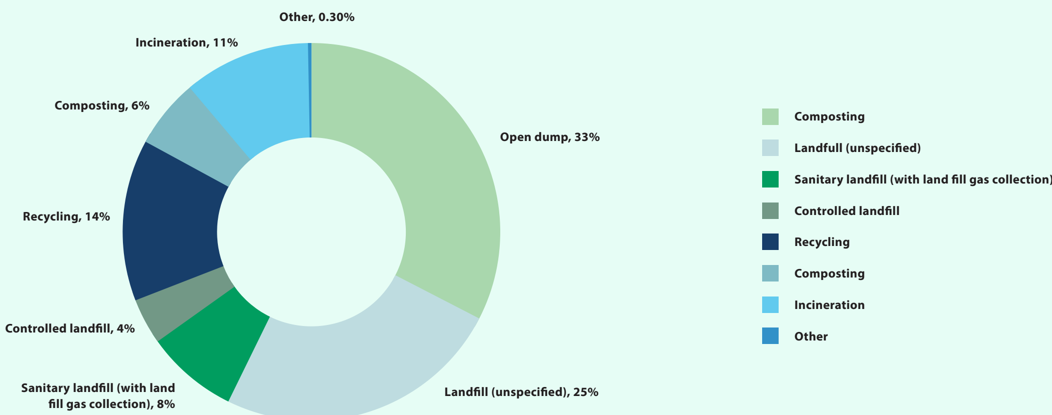
5. The World Bank: What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.

Greenhouse gas emissions from waste

A recent report by the World Bank on waste management and climate change estimated that globally, 1.6 billion MT of CO_2-equivalent[5] greenhouse gas emissions were generated from solid waste treatment and disposal in 2016. This represents approximately 5% of global emissions.

This is primarily driven by the disposal of waste in open dumps and landfills without landfill gas collection systems. Food waste accounts for nearly 50% of emissions. Solid-waste-related emissions are anticipated to increase by 63% to 2.6 billion MT of CO_2 equivalent by 2050.

The major greenhouse gas emissions from the waste sector are landfill methane (CH_4), wastewater methane and nitrous oxides (N2O). Methane is 30x more potent a greenhouse gas than carbon dioxide.



. [The World Bank: What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.]

Fig 8: *"Global treatment and disposal of waste, 2016, (in %)"*

Globally, most waste is currently dumped or disposed of in landfill. The highest emissions come from the one-third of all MSW disposed of in open dumps and the 25% in landfills with no control or landfill gas extracted from them.

Health impacts

If it is not collected and managed properly, waste poses a threat to public health and the environment. The United Nations considers proper waste management to be a 'basic human right,' alongside the provision of potable water, shelter, sanitation and food. Tackling waste management helps address more than half of the high-level sustainable development goals on the Post-2015 UN Development Agenda[6].

Waste collection is a critical step in the management of wastes. In high-income countries, waste collection is nearly universal. In low-income countries, waste collection in cities is around 48% on average. Outside cities, however, waste collection can fall to as low as 26%.

6. The World Bank: What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.

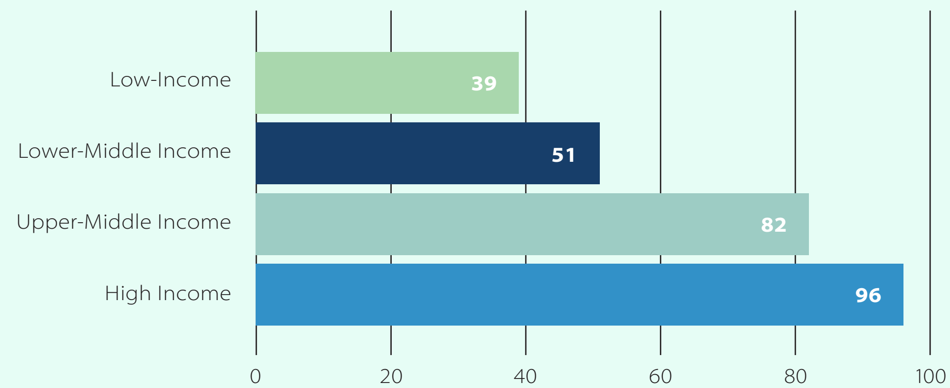


Fig 9: "Waste collection rates by income level (in %)"

. [The World Bank: What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.]

Not having a solid waste collection service has a direct impact on residents' health, especially children. For example, the uncontrolled burning of waste creates particulate and persistent organic pollutant emissions that are highly damaging to health.

Accumulated wastes can block drains and encourage the breeding of disease-carrying animals, which can be responsible for the spread of cholera and dengue fever, among other infectious diseases.

Uncontrolled dumpsites where MSWs mix with hazardous materials can contaminate the air, pollute surface and groundwater supplies and cause soil contamination.

According to the UN, diarrhea rates are twice as high in areas where waste is not collected regularly, and acute respiratory infections are six times as common.

An end to 'collect, sort, export'

Asian countries ban the import of much of the West's unwanted waste

Up until the end of 2017, China, Hong Kong and a number of other Asian countries had for twenty years imported more than half of the world's plastic and paper waste, predominantly from wealthy G7 countries as part of a now-defunct Western model branded "collect, sort, export." For Western countries, exporting waste, especially plastic and scrap paper, was cheap, helped meet 'recycling targets' and reduced sending waste to domestic landfills.

On December 31, 2017, China abruptly halted the import of many recycled materials from around the world. The ban was imposed on environmental grounds under a policy called "National Sword," which aimed at the improvement of public health. China will now only buy recycled plastic scrap that is 99.5% pure. Previously, contamination rates could reach up to 20%[7].

In Q4 2017, prior to the ban, China and Hong Kong imported 1.9 billion MT, or 59% of the 3.2 billion MT of plastic, paper and scrap waste exported from G7 countries. Forty-three percent (1.4 billion MT) of this came from European countries including the UK, Germany, France and Italy. Thirty-three percent (1.1 billion MT) came from the US and Canada.

For the receiving countries, a significant quantity of this waste was contaminated and could not be recycled. Some of it ended up in illegal waste processing centers, burned, and dumped into open rubbish dumps and waterways, creating significant environmental and public health problems.

Immediately following the Chinese ban, many Western countries thought the solution was to export their waste to other South East Asian countries. Within a year of the ban, overall G7 exports of waste fell by 28% to 2.3 billion MT. Asian destinations such as Malaysia, Vietnam, India, Taiwan and Thailand hugely increased their imports of Western waste. Sixty percent, or 1.4 billion MT of the total G7 waste, was imported by Asian countries (other than China) within a year of China's ban, compared with 17% prior.

However, a growing number of Asian countries, whose recycling systems have been overwhelmed to the point where they cannot cope from the deluge of western waste, have started to take a stand against waste "dumping" from wealthy western nations.

In March 2019, India banned all imports of solid plastic waste. Malaysia has revoked import permits and is clamping down on illegal processing plants. In May 2019, Malaysia sent back 3,000 MT of waste to the US, Canada, UK and several other European countries. The Philippines and Indonesia have begun to take similar action. Thailand has temporarily prohibited waste imports and will implement a full ban in 2021. Vietnam is no longer issuing new licenses and will prohibit all imports of plastic scrap by 2025. Taiwan has said it will only import single-source plastic waste.

7. BBC News article, 20 May 2019 "Could making recycling pay save the planet?" by Tim Harford

These actions by China and other leading Asian countries to stop taking waste generated by the wealthy west has left many Western countries scrambling to deal with a build-up of plastic and paper garbage in their own back yards. Several are having a serious re-think about how they will deal with a large portion of their domestically produced waste.

Changing attitudes and new opportunities: moving to a circular economy

Waste generation is increasing too fast. To solve this problem, the amount of waste generated needs to be decoupled from economic growth and living standards. Economies must become more circular, with the "take, make, dispose" model shifting to a "reduce, re-use, recycle" model. The circular economy must allow people to make money in order to succeed.

Attitudes toward the processing of waste are beginning to shift. The concept of the circular economy is beginning to solidify itself as an alternative to the linear economy, where resources are extracted (often from the ground), made into to short-life products, used for a brief period and then thrown away, in many cases to be buried in landfills.

The circular economy sees resources kept in use for as long as possible, the minimum value extracted from them while in use, and the products and materials recovered and regenerated at the end of each service life.

A circular economy can have several benefits:

- Creates new opportunities for growth in the extraction of value from waste
- Leads to an overall reduction in waste
- Drives greater resource productivity
- Delivers a more competitive economy
- Can help position a country to better address emerging resource scarcity and security issues in the future
- Can reduce environmental impacts of production and consumption

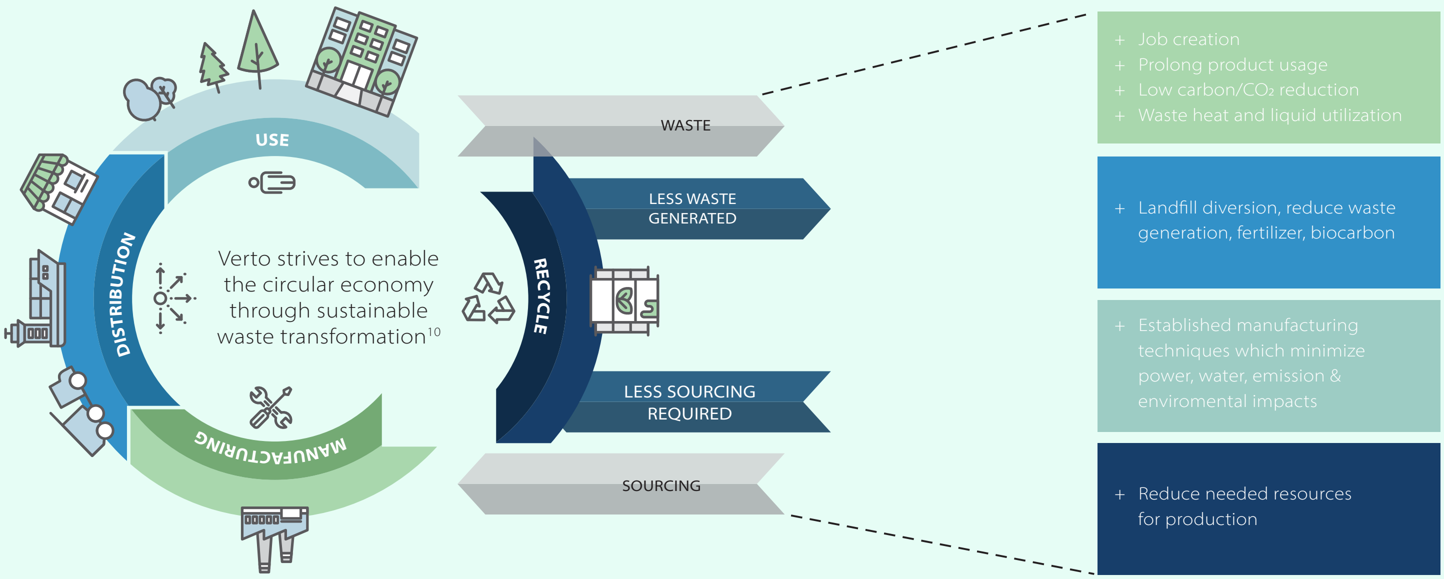


Fig 10: *"The Verto view of the Circular Economy"*

Politicians and public around the world appear increasingly attentive to the economic, ecological, and human costs of waste, as well as the missed opportunity (value) it represents. Many western governments are crafting 'circular' strategies. By 2035, for example, all EU states will be required by law to recover 65% of their waste—up from an average of around 40% today.

Austria has the world's highest recycling rate, with 63%[8] of all waste diverted from landfills. Germany is at 60%, and Taiwan and Singapore are examples of countries achieving relatively high rates of waste recycling, at 59% in 2016 (67% in Taiwan's capital, Taipei). South Korea recycles 49%.

Entrepreneurs see waste as an opportunity—the re-purposing of waste into something people are willing to purchase. Waste becomes something of value. In several situations, this can be done profitably and at scale.

For some materials this is already achieved: glass, aluminum, copper and other metals are examples.

Progress is also being made in the world's most common form of waste: food waste, which accounts for 43% of all waste. Anaerobic Digestion (AD), where organic matter is broken down by microbes in the absence of oxygen, produces biogas that can be burned to create energy and heat. Between 2009 and 2016, the number of AD plants grew from 6,000 to 17,700. AD produces 2% of the EU's electricity, but the figure seems poised to grow, as governments look to tackle food waste and encourage renewable energy generation.

8. General Kinematics: Top 10 Recycling Countries from around the world

Plastics remain a major problem. Polymers from petroleum are cheap, but they can be costly to extract from the waste stream. However, the global public outcry over plastic pollution is concentrating policy makers' minds. China's recycling import ban has further forced a re-think in source markets. Fiscal incentives and policy rules that force manufacturers to maintain a minimum recycled content in plastic containers (extended producer responsibility) are likely to increase in the recycling of future plastics.

9. Alliedmarketresearch: Waste Management Market Outlook - 2025

Waste-to-Value

The global waste management market size is expected to increase from US $330 billion in 2017 to US $530 billion by 2025, growing at 6.0% CGAR[9]. Increased environmental awareness, rapid industrialization, and a rise in urbanization foster the growth of the global waste management market. In addition, the implementation of stringent government regulations on open dumping is expected to fuel the waste management market's growth.

Examples of Waste-to-Value inputs and outputs comprise the following:

Waste-to-Energy:

- Biomass (wood pellets) to power, heat & CHP
- Refuse Derived Fuel (RDF) to power, heat & CHP
- Solid Recovered Fuel (SRF) to power, heat & CHP
- Incineration of MSW fractions to power, heat & CHP

Waste-to-Fuels:

(i) Solid fuels

- Wood residuals/sustainable logs to wood pellets (as a fuel)
- MSW to RDF/SRF (as a fuel)

(ii) Gases

- Anaerobic digestion (organic waste to electricity, heat, fertilizer)
- Landfill gas (electricity, heat, vehicle fuel)

Waste-to-Materials

(i) Recycled products

- End-of-life wind turbine blades-to-thermo-plastic pellets

(ii) Packaging

- Single-use plastic bottles to sustainable filament yarn (polyester) for apparel manufacturing

(iii) Chemicals

- Waste (MSW)-to-bio-methanol (for chemical feedstock & vehicular fuels)
- Biomass & MSW-to-jet fuel

(iv) Other

- MSW-to-commercial composting (3 different methods) for fertilizer

Section 2

Analysis & Overview of the Waste Market Opportunity in Verto's Key Markets in North America & Europe

Europe
Analysis of the EU waste market

Europe, particularly the EU, is one of the world's most progressive and proactive regions in terms of environmental awareness, regulation and positive action. In the waste market, European countries have increasingly shifted focus over the last two decades with regard to waste streams, from disposal methods to prevention and recycling, and adherence to the Waste Hierarchy.

The Waste Hierarchy ranks waste management options according to what is optimal for the environment and factors in the economic value of waste and principles of a circular economy. Its aim is to extract the maximum practical benefits (including economic value) from products and generate the minimum amount of waste.

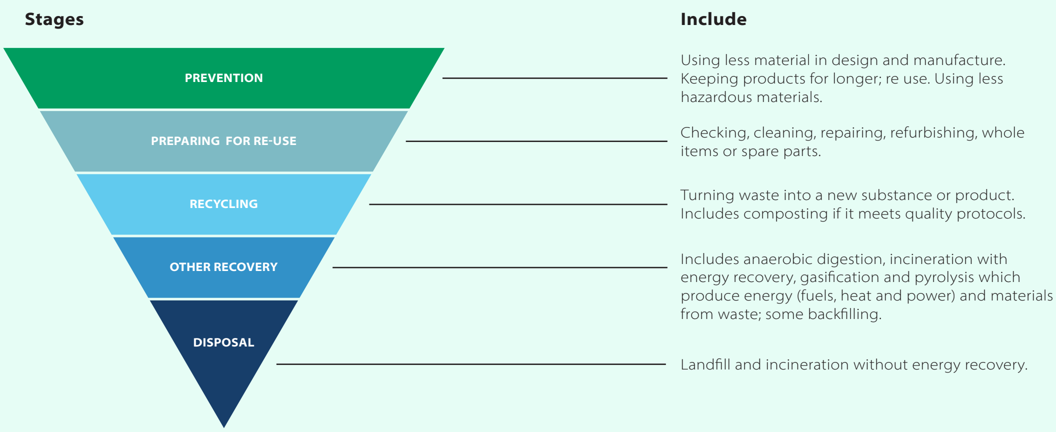


Fig 11: "The Waste Hierarchy"

. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69403/pb13530-waste-hierarchy-guidance.pdf

The Waste Hierarchy gives top priority to preventing waste in the first place. When waste is created, it gives priority to preparing it for re-use, then recycling, then recovery. This creates profit from waste streams, which can include electricity generation, heat, materials and other valuable products. The last and least-desirable option would be landfilling.

10. EuroStat: Waste Statistics - Statistics Explained

Total EU waste, by all economic activities and households

In 2016, total waste generated in the EU-28, with a population of 510 million, by all economic activities and households, amounted to 2,538m MT[10]. Of this, the largest amount of wastes came from construction and demolition (36.4%, 923m MT), followed by mining and quarrying (25.3%, 642m MT). Household waste was 8.5% (which accounts for a large part of, but not all MSW), at 215.7m MT.

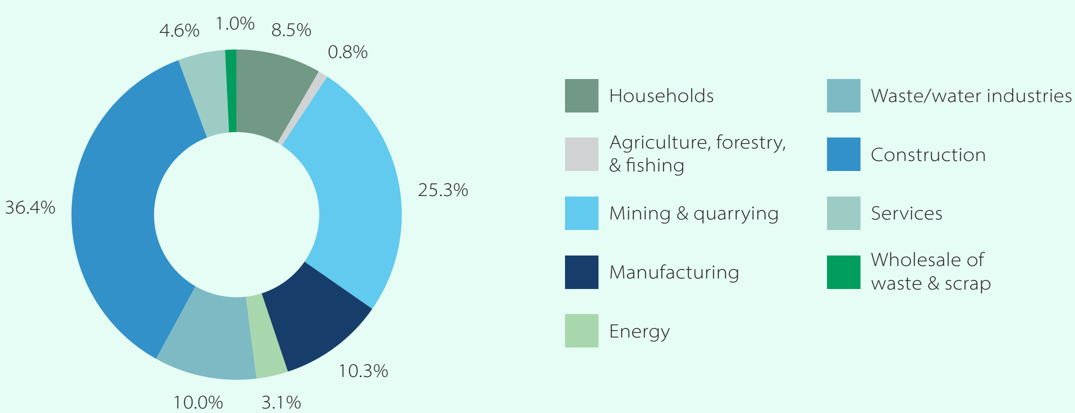


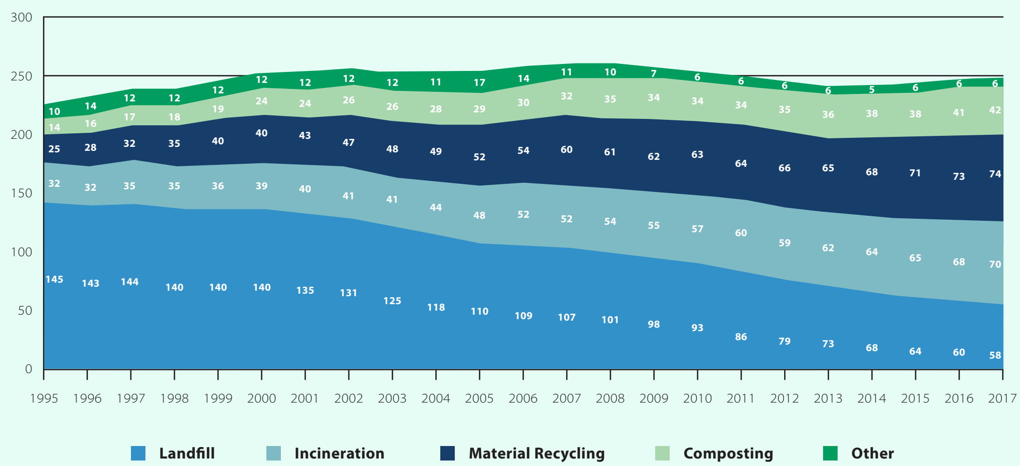
Fig 12: "EU-28 total waste generation by economic activity and households, 2016 (%)"

. https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1183.pdf

Municipal Solid Waste in the EU

Although MSW (household, office and commercial waste) accounts for only around 10% of total waste generated (approximately 249m MT in 2017), it has a very high political profile because of its complex character, its composition, its distribution among many sources of waste and its link to consumption patterns.

Over the last two decades, European countries have increasingly shifted their focus about MSW from disposal methods (predominantly landfilling) to prevention and recycling. Moving MSW up the Waste Hierarchy is seen as essential in extracting more value from resources while reducing pressure on the environment.



. https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics#Municipal_waste_generation

Fig 13: "Municipal Solid Waste: landfilled, incinerated, recycled and composted, EU-28, 1995-2017"

The graph shows MSW generated in the EU-28 countries in the years between 1995 and 2017 and how that waste has been treated, including landfilling, incineration, recycling, composting and other.

Total municipal waste generated fluctuated from 227m MT in 1995 to a peak of 261m MY in 2007/8 and stood at 249m MT in 2017.

Trends in MSW treatment

Some clear waste treatment trends can be observed over this 23-year period:

(i) Waste going to landfills **fell by over 60%**, from 145m MT in 1995 to 58m MT in 2017. This was driven by several factors, including the Waste Hierarchy, regulatory targets for recycling and energy recovery, and the imposition of landfill taxes. Today, 24 out of 28 EU countries have a landfill tax, however charges vary widely from €3/MT in Latvia to €113/MT in Belgium[11].

(ii) **Recycling of MSW has increased by 195%** over the period.

(iii) **Composting has grown by 196%** in the period. Food and agricultural wastes can generate energy, heat and fuels via anaerobic digestion (AD) processes, in addition to generating revenue from fertilizer, made from AD digestate. Fertilizer can also be produced from commercial composting operations.

(iv) **Incineration (with energy recovery) increased by 118%** in the 1995-2017 period. This is driven by a combination of landfill taxes and the fact that energy and heat can be recovered via incineration.

11. http://www.cewep.eu/wp-content/uploads/2017/12/Landfill-taxes-and-bans-overview.pdf

12. European Parliament, Circular Economy Package

Waste treatment of Municipal Solid Waste in EU-28, in 2017

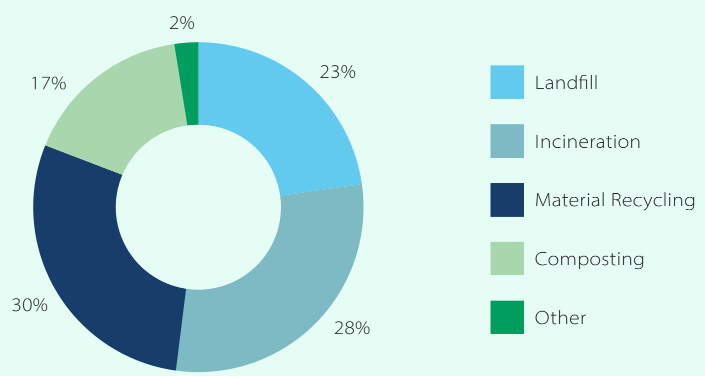


Fig 14: "Waste treatment of Municipal Solid Waste in EU-28, in 2017"

. https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics#Municipal_waste_generation

The graph above shows the treatment of municipal waste in 2017 across the 28 EU countries.

Several improvements were observed over the period. Overall, municipal **waste per capita in the EU decreased by just over 9%**[12] from 523kg in 2007 to 474kg in 2014, though this is partly attributed to the financial crisis.

Landfilling of waste fell from 64% of all MSW in 1995 to 23% in 2017, demonstrating the success of EU policies and targets to encourage diversion from landfills to other types of waste management options higher up the Waste Hierarchy (see EU Regulatory Drivers, on the following page).

The combination of **material recycling** (e.g. glass, metals, paper and some plastics) **and composting** (which includes treatment of waste food, garden and agricultural wastes) via AD and commercial composting **increased from 17% in 1995 to 46% in 2017**.

Materials recycling alone (without composting) increased from 11% in 1995 to 30% in 2017.

Incineration of MSW has **doubled from 14%** in 1995 to **28%** in 2017.

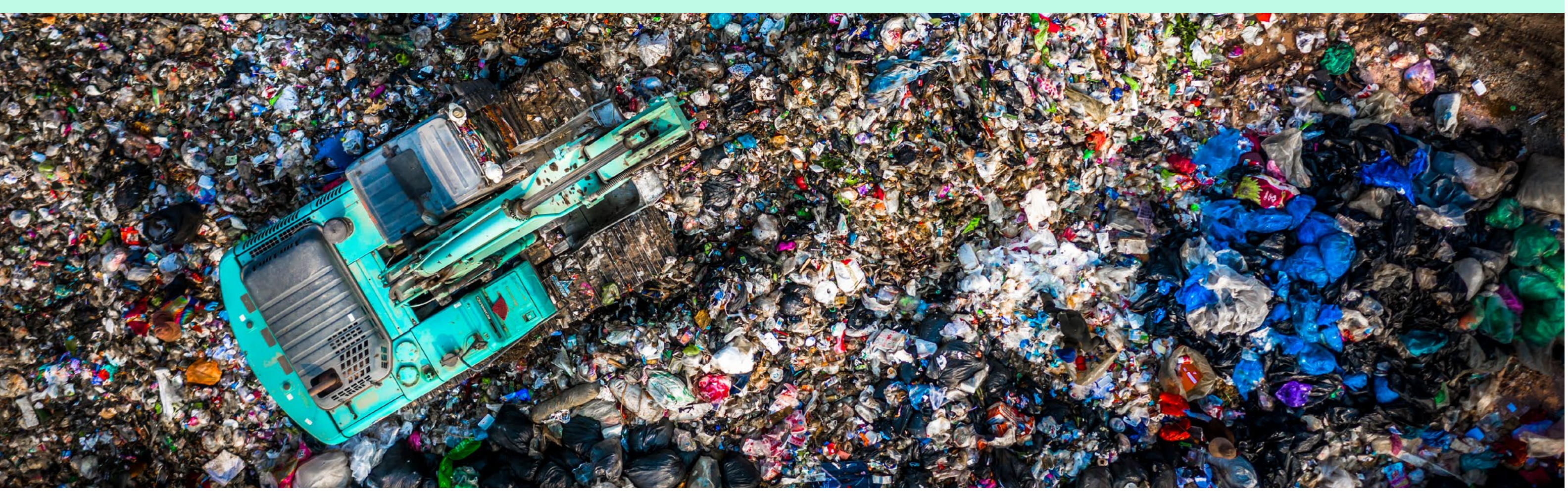
While over the past two decades, substantial progress has been made in overall waste management, particularly the diversion of waste from landfills, almost a quarter of municipal waste was still sent to landfills at the end of 2017, and less than half was recycled or composted. This leaves substantial future opportunities for extracting higher value in terms of material resources from these waste streams.

EU market drivers: regulatory, economic, technology, social impact

(i) EU regulatory drivers[13]

Waste policies and targets set at the EU level include minimum requirements for managing certain types of waste. The EU's approach to waste management has moved from simply reducing environmental and human health complications to placing a greater emphasis on effective waste treatment as an important and valuable resource, and the embracing of a circular economy.

13. Summary of current EU waste legislation



The most relevant policies and targets for municipal waste are:

1994 PACKAGING AND PACKAGING WASTE DIRECTIVE (1994/62/EC)

This directive set out to harmonize measures and requirements for the prevention, re-use and recovery of packaging wastes across EU member states. Requirements focused on the need to:

- Limit weight and volume of packaging to a minimum
- Reduce the content of hazardous substances
- Design reusable and recoverable packaging
- Implement the producer responsibility principle

1999 LANDFILL DIRECTIVE (1999/31/EC)

The 1999 Landfill Directive (effective July 2001) regulated the waste management of landfills. Its aim was to prevent or reduce pollution and environmental impacts of surface and ground water, soil, air and greenhouse effects from the landfilling of wastes, during the whole life cycle of landfills. Landfills are divided into three classes: landfills for (i) hazardous waste, (ii) non-hazardous waste and (iii) inert waste.

The directive banned certain types of wastes from being landfilled (including liquids, flammable and explosive wastes, hospital/clinical wastes and tires with certain exceptions). These wastes would have to be recovered, recycled or disposed of in other ways. It also required waste to be treated before being landfilled and the use of separate landfills for hazardous wastes.

Key targets were set: the amount of biodegradable municipal waste being sent to landfills must be reduced to 50% by 2009 and to 35% by 2016 (compared to 1995 levels).

2008 WASTE FRAMEWORK DIRECTIVE (*WFD*) (2008/98/EC)

The principal aim of the WFD was to lay out the blueprint for turning the EU into a recycling society.

Two new recycling and recovery targets were introduced, to be achieved by 2020:

(i) *50% (by weight) preparing for re-use and recycling of certain wastes materials* ***from households*** *(e.g. paper, metal, plastic and glass).*

(ii) *70% (by weight) preparing for re-use and recycling of certain wastes materials* ***from construction and demolition waste.***

The WFD distinguished when waste ceases to be waste and becomes a secondary raw material. One of the key features was the **Waste Hierarchy**. This prioritizes (i) waste prevention, followed by (ii) preparing for re-use, (iii) recycling and other recovery, and finally (iv) disposal or landfilling (the least desirable option).

The WFD introduced the **Polluter Pays Principle and Extended Producer Responsibility** for packaging. This shifts the waste management cost of product packaging, wholly or partially, from local governments to producers.

In 2015, the European Commission adopted the Action Plan for the Circular Economy (COM (2015) 614). This contained a vision and a list of concrete actions to help the whole value chain move towards a circular economy. This includes design and production, across consumption, and into waste and secondary raw materials management.

2018 CIRCULAR ECONOMY PACKAGE

In June 2018, The EU Council of Ministers adopted new rules for waste management, establishing binding targets as part of the Circular Economy Package. This package updated the Waste Framework Directive, Landfill Directive, Waste Packaging and Packaging Waste Directive and other key pieces of EU waste legislation.

- By January 1, 2025, member states must have separate household collections of textiles and hazardous wastes
- By December 31, 2023, bio-waste will have to either be collected separately, or recycled at source
- By 2020, preparation for the re-use and recycling of paper, metal, plastic and glass from households (and similar) to be a minimum of 50% by weight

As an update to the Landfill Directive, member states must adhere to the following targets:

- Share of municipal waste that can be landfilled: 2030: 10%[14*]

Other targets, outlining the share of waste to be prepared for reuse and recycling at end-2025 and end-2030, included:

- Municipal waste
  60% 65%
- All packaging waste
  65% 75%
- Plastic packaging waste
  55% **
- Wood packaging waste
  60% 75%
- Ferrous metal packaging waste
  75% 85%
- Aluminum packaging waste
  75% 85%
- Glass packaging waste
  75% 85%
- Paper and card packaging waste
  75% 85%

14. European Parliament, Circular Economy Package

* *7 members states were given 5 additional years to reach this target*

** *No 2030 target has been set for plastic packaging. The EU Commission may set one at a later stage based on a progress review, the evolution of the plastic packaging market and the development of recycling technologies.*

(ii) Economic drivers

(a) LANDFILL TAX

Landfill taxes have proven a highly effective economic driver in the EU to divert waste from landfills and encourage other solutions for waste management higher up in the Waste Hierarchy, including re-use, recycling, composting (including AD) and energy recovery (incineration).

A landfill tax is a levy applied in some countries to place waste in landfills. The tax is commonly applied on a cost-per-MT basis in addition to the cost imposed by the landfill operator, forming a proportion of the overall "gate fee" of disposing of waste in a landfill.

For example, a landfill tax was first introduced in the UK in 1996 at £7/MT for standard waste. In 2008, the government induced an £8/MT annual escalator until 2014. Currently, the standard landfill tax rate is £91.35/MT. It will increase again on April 1, 2020 to £94.15[15].

15. https://www.360environmental.co.uk/legislation/waste_legislation/landfill_tax and https://www.letsrecycle.com/news/latest-news/landfill-tax-rate-rises-to-91-35-per-tonne/

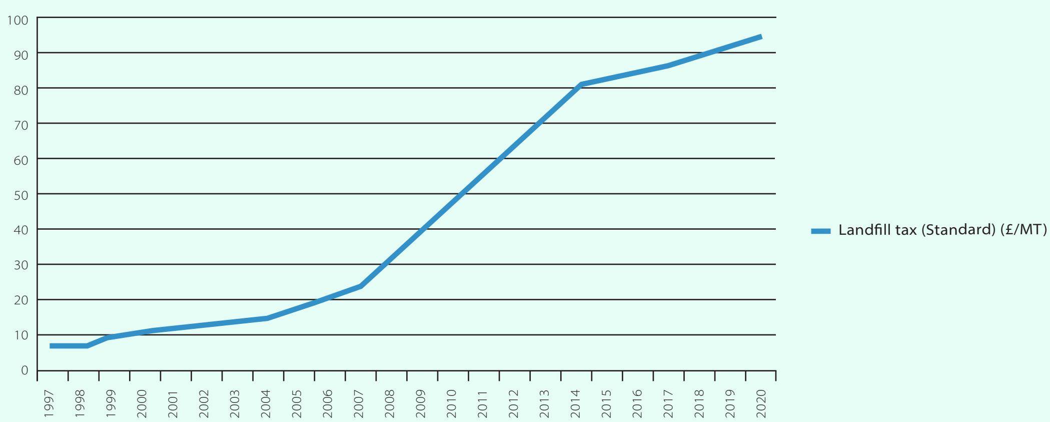


Fig 15: *UK landfill tax (standard, in £ per MT) 1997-2020*

. https://www.360environmental.co.uk/legislation/waste_legislation/landfill_tax/

. https://www.letsrecycle.com/news/latest-news/landfill-tax-rate-rises-to-91-35-per-tonne/

The increase in UK landfill taxes in the years following 1997 is directly correlated with the reduction in tonnage of waste going to landfills over the following two decades. Total waste going to landfills in the UK has reduced by approximately 70% between 1997 and 2015, from 95m MT to 28m MT.

UK Government landfill tax receipts peaked in 2013/14 at just under £1.2 billion.

In the wider EU, 24 of the 28 member states have landfill taxes, however these vary widely, from €3/MT in Latvia to €113/MT in Belgium (in 2017)[16].

16. Confederation of European Waste to Energy Plants (CEWEP).

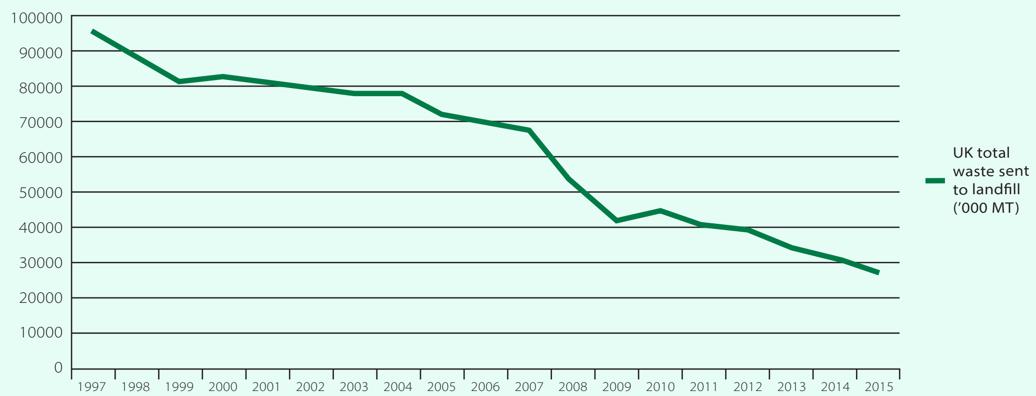


Fig 16: *Total waste sent to landfills in UK (in '000 MT)*

. http://www.localis.org.uk/news/waste-management-and-brexit-a-chance-to-re-think-strategy/

(b) FINES

If EU countries do not adhere to EU directives, including those relating to waste, they can be fined by the European Court of Justice.

An example of this was in 2014, when Italy was ordered to pay a lump sum penalty of €40m and a further penalty of €42.8m for each six months it delayed taking necessary measures, with a judgment mandated in 2007.

The court established Italy had failed to comply with its waste management obligations under directives on waste, hazardous waste and the landfill of waste. In particular, 218 sites in 18 of the 20 Italian regions were not in conformity with the Waste Directive, a number were in breach of the Hazardous Waste Directive, and a small number of landfills had not been conditioned or closed down in accordance with the Landfill Directive.

(c) LAWS TO INFLUENCE CONSUMER BEHAVIOR - 5P PLASTIC CARRIER BAG CHARGE

Member states have introduced financial measures to influence consumer behavior and help prevent waste. An example of this was the UK's October 2015 introduction of a law requiring supermarkets and large stores to charge a minimum of 5p for every single-use plastic carrier bag. This is due to increase to 10p in January 2020.

The carrier bag levy was introduced to reduce their reliance and the litter they cause. In 2014, 7.4 billion single-use plastic carrier bags were handed out in the UK, equivalent to 140 per person, per year. Environmental campaigners claim it can take up to 1,000 years for them to break down.

The impact of the levy has been very significant. Carrier bags issued by large supermarkets have declined by 86% since the charge was introduced. In 2017-18, 1.7 billion were issued, down from 7.7 billion in 2014.

(d) ECONOMIC BENEFITS FROM A CIRCULAR ECONOMY

Boost to GDP
Several studies have estimated the benefits of fully embracing a circular economy. One such study, conducted by the Waste Resources Action Program (WRAP), in conjunction with The Prince's Responsible Business Network (PwC) for Business in the Community, estimates that enhanced productivity and economic growth as a result of a circular economy in the UK could result in an increase in GDP of 8% by 2050[17]. This includes growth in GDP per employee of between 10 and 15%.

Boost to innovation and investment
Benefits include encouraging investment and innovation, such as the application of digital, machine-leading and robot technologies, which could increase innovation and investment in the companies selling products and services, in addition to those in the waste and materials management sectors.

Improvement to the balance of trade
The circular economy could improve the balance of trade. The cost of components and materials are typically 40-60% of total costs and many are imported into the UK. The UK's current deficiency in goods and services is around 7%. The study forecasts that a materially efficient circular economy could improve the country's trade balance by 1-2% of GDP.

Boost to jobs
The analysis suggests that a circular economy could generate over 200,000 jobs (gross) in the period to 2030, across regions of the economy where there are higher rates of unemployment.

Reducing greenhouse gases
Modeling at the EU level, the study suggests a circular economy could lead to a material reduction in greenhouse gas emissions. A reduction in landfilling, reuse and recycling of materials could lead to a reduction in raw material extraction and the manufacturing of petroleum-based products such as plastics.

17. WRAP/Business in the Community: Smart Growth, the economic case for the circular economy

(iii) Technological drivers

There are several technologies being developed, trialled and utilized in the waste management sector of developed countries. Below, some of the key ones are listed.

ADVANCED THERMAL TREATMENT TECHNOLOGIES:

Pyrolysis

Pyrolysis is the thermal decomposition of biomass at elevated temperatures occurring in the absence of oxygen. The products of biomass pyrolysis include biochar, bio-oil and gases, including methane, hydrogen, carbon monoxide and carbon dioxide.

At temperatures of less than 300˚C-450˚C, when the heating rate is quite slow, pyrolysis will yield mainly bio-char. At temperatures greater than 800˚C, mainly gases are produced. At intermediate temperatures, bio-oil is produced.

Pyrolysis can be performed at a relatively small scale. It offers a flexible means for converting solid biomass into an easily stored and transported liquid, which can be used to produce power, heat and chemicals.

A wide range of biomass feedstocks can be used in pyrolysis processes, such as agricultural residues, wood-based residues and short-rotation crops. Moisture content should be around 10%.

Pyrolysis processes can be categorized as slow pyrolysis or fast pyrolysis. Fast pyrolysis is the most common, yielding 60% bio-oil, 20% biochar and 20% syngas.

Pyrolysis can be used to treat plastic wastes, with the main advantage being the reduction in volume. In tire recycling, tire pyrolysis is a well-developed technology. Products from car tire pyrolysis include steel wires, carbon black and bitumen.

Gasification

Gasification can be considered a process between pyrolysis and combustion that involves partial oxidation of a substance. This means oxygen is added, but the amounts are not enough for the fuel to become completely oxidized, allowing for full combustion to occur.

Gasification generally occurs above 650˚C. Raw MSW would not be a typical candidate for gasification, as it would require the separation of glass, metals and inert materials (such as rubble).

The main product is syngas, which contains methane, hydrogen and carbon monoxide.

A key issue when using the syngas in energy recovery at advanced thermal treatment facilities is tarring. Deposition of tars can cause blockages and other operational challenges. A syngas clean-up or 'polishing' is sometimes required before the syngas is utilized for energy recovery.

Plasma Arc Gasification (PAG)

PAG is a waste treatment technology that uses a combination of electricity and high temperatures to turn MSW into usable by-products without combustion.

PAG converts organic waste into a gas that keeps its chemical and heat energy intact and converts the inorganic waste into an inert, vitrified glass called slag. The process can reduce the volume of waste sent to landfills and generate electricity.

In the PAG process, an electrical arc gasifier passes a very high voltage electrical current through two electrodes, creating an arc between them. Inert gas, which is under high pressure, then passes through the electrical arc into a sealed container (called a plasma converter) of waste materials. Temperatures in the arc column can reach more than 14,000˚C—hotter than the surface of the sun.

The waste is transformed into a gas—a mixture of predominantly hydrogen and carbon monoxide. Before the syngas can be used for energy recover, it must be cleansed of hydrogen chloride.

PAG appears to offer significant potential for reducing landfill waste and converting waste into useful energy. However, its high costs and uncertain environment impacts have complicated efforts to build commercial facilities.

Small facilities are operating in several countries to dispose of hazardous material such as chemical weapons[18].

(iv) Social / impact drivers

In the EU, recent years have seen a heightened awareness of the impact of waste and the negative impacts it can cause in the local and global community. This is leading to an increasing shift in attitude and culture as it pertains to consumer choices and how the public, companies and government (local and central) view the handling of waste.

Plastics - *public opinion turns against single-use plastics*

Plastic is everywhere, and suddenly everyone has decided it's a very bad thing. Decades after becoming an integral part of the fabric of our lives, a worldwide revolt against plastics is under way[19]. While it's seen as very useful for consumption, from an environmental point of view, only a fraction of plastic is recycled, and it can take up to 1,000 years to decompose in landfills.

18. https://www.britannica.com/technology/plasma-arc-gasification

19. The Guardian: "The plastic backlash: what's behind the sudden rage - and will it make a difference?", 13 November 2018

In 2018, National Geographic reported 8.3 billion MT of plastic that has been produced globally over the past 60 years, 6.3 billion MT has become plastic waste. Of that, only 9% has been recycled, 12% has been incinerated and 79% has accumulated in landfills or in the natural environment (including in the world's oceans) as litter[20].

A report published in 2014 by a collaborative group of scientists, following 24 expeditions across the world's oceans, estimated there are more than 5 trillion[21] pieces of plastic, weighing over 250,000 MT afloat in the world's seas and oceans.

In recent years, several TV programs and high-profile campaigns have significantly raised awareness.

"Sky Ocean Rescue," launched in January 2017, is a campaign that shines a spotlight on issues affecting ocean health, finding innovative solutions to ocean plastic contamination and inspiring people to make small changes in their everyday lives to make a difference in the world.

The final episode of **David Attenborough's** exploration of the world's oceans in the **2017 BBC series "Blue Planet II"** was described by the Financial Times as a "bombshell" in terms of plastic pollution awareness, and is credited with causing a ripple reaction with the public with respect to their understanding of the damage plastic pollution is doing to the world's oceans and its inhabitants.

The 2019 BBC series "War on Plastic," presented by environmental campaigner Hugh Fearnley-Wittingstall, recruited the inhabitants of a typical street in Bristol to study how many single-use plastic items households utilize and how easy (or difficult) it is to reduce or eliminate them in daily life. It also explored where all Britain's recycling ends up, concluding 665,330 MT is exported to 12+ countries, a significant amount of which is shipped to Malaysia, where much remains untreated, while some ends up in illegal reprocessing and open-air burning operations.

Recycling - *people want to do their bit, but the system is challenging and confusing*

Surveys show public support for recycling and efficient use of resources across the EU and in the UK is very high[22]. However, surveys also show there is a significant amount of confusion about what can and what cannot be recycled.

Current systems: both local government recycling regimes and producer packaging recycling instructions do not make it intuitive. For example, in the UK, there are 408 local council authorities. Each is responsible for waste collection, yet amongst these authorities, there are 39 different sets of rules for what can be put in plastic recycling collections[23].

20. National Geographic: "A whopping 91% of plastic isn't recycled"
21. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0111913
22. European Commission: Attitudes of Europeans towards waste management and resource efficiency
23. BBC News: Why plastic recycling is so confusing, December 2018

Some local authorities collect all recycling in one bin, while others ask for waste to be segregated with anything from 2-6 different bins, with separate bins for:

- Paper and card
- Metals, glass and plastics
- Waste food
- Garden waste
- Everything else

Fig 17: "Plastic packaging recycling symbols"

. https://www.bbc.co.uk/news/science-environment-45496884

A 2019 study by consumer charity Which?, carried out in five major UK supermarkets, found almost half of all packaging cannot be easily recycled. With respect to recycling instructions on packaging, 42% was found to be labeled incorrectly or not at all.

The principal confusion seems to be around what plastic items can be recycled. For some items, there is almost universal collection, e.g. detergent bottles, milk bottles, plastic drinks bottles. Approximately three quarters of UK authorities will recycle margarine pots, yoghurt and food tubs. However, less than one quarter of authorities currently recycle black plastic (ready meal) trays, carrier bags, cling film, plastic pouches and polystyrene packaging. Dirty or contaminated plastics will commonly not be recycled.

Recycling symbols on packaging can also be highly perplexing.

The EU target for recycling across the EU is 50% by 2020. The UK recycling rate for waste from households was 45.7% in 2017[24], close to the EU average of 46% (for MSW recycled materials and composting).

24. UK Statistics on Waste, March 2019

Government action

In August 2018, following a UK Treasury call for evidence and more than 162,000 responses, the UK government said there was widespread public support for reducing single-use plastic waste through possible measures such as:

- The introduction of a "latte levy" on coffee cups, like the plastic bag charge, and tax incentives for recycling
- Encouraging greater use of recycled plastic in manufacturing
- Discouraging the use of difficult–to-recycle plastics such as carbon black plastic
- Examining a ban on plastic straws, stirrers and cotton wool buds
- Introduction of deposit return schemes to encourage recycling

The UK Government's 2018 Resources and Waste Strategy for England outlines a strategy to preserve material resources by minimizing waste, promoting resource efficiency and moving towards a circular economy. This aims to keep resources in use if possible, to extract maximum value from them.

Key recommendations included:

- Sustainable production: invoking 'polluter pays' principle, ensuring producers pay the full costs of disposal for packaging they place on the market and a tax on plastic packaging with less than 30% recycled plastic
- Helping consumers choose more sustainable products
- Driving a better quantity and quality of recycling with more investment in domestic recycled materials markets.
- Promoting UK-based recycling by ensuring a consistent set of dry recycled materials is collected from all households and businesses while exporting less waste to be processed abroad
- Tackling waste crime, e.g. illegal dumping and illegal waste exporting
- Reducing food waste
- Promoting the goals of resources and waste strategy internationally
- Supporting investment and innovation
- Ensuring high-quality data, monitoring and evaluation

The UK Plastics Pact

In April 2018, The UK Plastics Pact was launched by the not-for-profit Waste Resources Action Program (WRAP). This Pact was backed by the UK Government and supported by a coalition of 42 mainstream businesses from across the plastic value chain. These companies, which include Nestle, M&S, Unilever, P&G, and PepsiCo, were responsible for more than 80% of plastic packaging found in products sold in UK supermarkets at the time of launch.

The goal is to make unnecessary single-use plastic "a thing of the past by improving recyclability, championing re-use and promoting plastic-free innovations." It is intended to be a collaborative initiative that will create a circular economy for plastics. It brings together businesses from across the entire plastics value chain with UK government and NGOs to tackle plastic waste.

Key targets are, by 2025[25]:

- One hundred percent of plastic packaging to be reusable, recyclable or compostable
- Seventy percent of plastic packaging effectively recycled or composted
- Eliminate problematic or unnecessary single-use packaging items through re-design, innovation or alternative (re-use) delivery models
- All plastic packaging to contain 30% average recycled content

25. http://www.wrap.org.uk/content/the-uk-plastics-pact

Since launch, the Plastics Pact has grown to 127 members and now includes waste management companies, local authorities, universities and SMEs.

Significant progress has been made in the first year by several of the major corporate signatories in each of the four goals, for example:

- Several supermarkets phasing out black plastics from their products
- Some phasing out a use of polystyrene
- Some removing plastic from teabags
- Many have agreed to put clearer recycling labeling on packaging
- Some increased recycled content in packaging such as plastic bottles

On the one-year anniversary of the launch of the Pact, WRAP's CEO, Marcus Gover, praised the progress that has been made but said there is a lot further to go, including "new innovations to foster, investment to be made - all at a great pace and with an urgency that reflects the scale of the problem."

North America

Analysis of the US Waste Market

All waste generation

According to the US public interest research organization Frontier Group, the US produces more than 30% of the planet's total waste-per-year (approximately 8.7 billion tons in 2015 across all economic activities), while accounting for only 4% of the world's population[26]. Most of the total waste is generated from industrial processes such as mining, manufacturing and agriculture. Municipal waste accounts for just 3% of all US waste.

Municipal Solid Waste Generation

Total MSW in the US in 2015 was 262.4m tons[27]. This amounts to 4.48lb (2.03kg) per person, per day. US citizens produce 3 times more waste per day than Chinese citizens, and 7 times more than people in Ethiopia.

Globally, the US produces 12% of the world's total MSW, with 4% of the population.

The following graph shows the growth in US MSW generation between 1960 and 2015.
Over the entire period, the amount of waste grew by 198% from 88.1m tons to 262.4m tons.

26. Frontier Group, "Trash in America: Moving from destructive consumption to a Zero-Waste System"

27. US EPA: "Facts and Figures about Materials, Waste and Recycling"

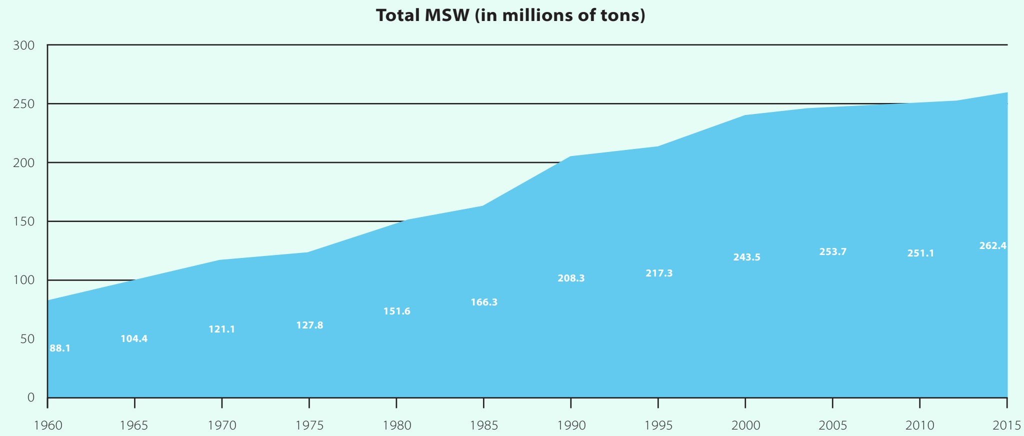


Fig 18: Graph: "US MSW Generation (in millions of US tons)"

. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

Meanwhile, population growth increased by 77% from 180.7m in 1960 to 321m in 2015, reflecting an increase in per capita waste generation.

Per capita waste generation grew between 1960 and its peak in 2000 from 2.68lb (1.2kg) to 4.74lb (2.2kg) per person, per day. By 2015 it had fallen slightly to 4.48lb (2.0kg)/person/day.

The following graph shows the composition of MSW in the US in 2015. Paper and paperboard made up the largest portion of MSW, amounting to 26% of all MSW (68.1m tons) in 2015. Tonnage of this category fell by 20% between 2005 and 2015 as a result of digitization of news and electronic transmission of documents and reports. Food waste was the second largest component, at 15%.

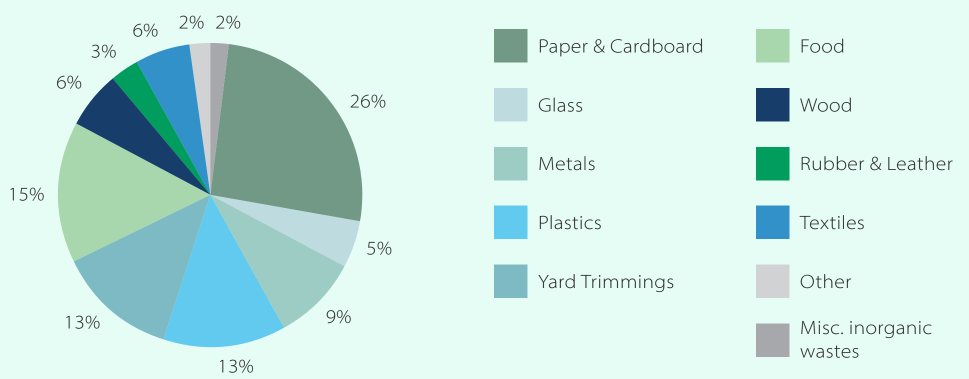


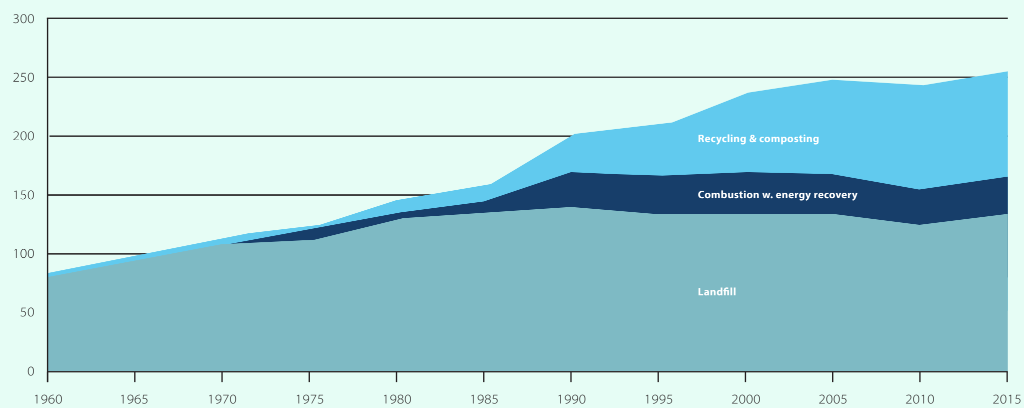
Fig 19: "Composition of US MSW in 2015"

. https://www.epa.gov/sites/production/files/2018-07/image2_0.png

Yard trimmings were the third highest component of MSW composition. This accounted for 17% in 1990 but fell to 13% by 2015 due to state legislation discouraging yard trimmings disposal in landfills and the promotion of backyard composting.

Plastics waste generation grew from 8% of all MSW in 1990 to 13% in 2015, amounting to 34.5m tons.

Treatment of Municipal Solid Waste



. https://www.epa.gov/sites/production/files/2018-07/image1.png

Fig 20: *""Treatment of U.S. MSW 1960-2015"*

Landfilling accounted for 52% of all MSW waste treatment in 2015, at 135m tons. Landfilling of waste has remained relatively constant in tonnage terms since 1980, between 134m tons and 143 tons over the 30-year period. In 2015, food was the largest component of landfilled waste, at around 22%. Plastics accounted for 19%, paper and paperboard 13%, and rubber, leather and textiles 11%.

Recycling and composting together accounted for 35% of MSW treatment in 2015. This has increased steadily since 1990, when it accounted for just 16% of waste treatment, though the US remains the developed world's worst performers in terms of recycling and composting.

Recycling of materials accounted for 26% of US MSW (67.8m tons) in 2015. Of this, paper and paperboard were 67%, metals were 12% and glass, plastic and wood were approximately 4.5%.

Composting was 9% of MSW (23.4m tons) in 2015. Of this, 91% was yard trimmings, while 9% was food waste.

Combustion with energy recovery (incineration) in 2015 accounted for 13% of MSW treatment (33.6m tons). Of this, food was 22%, rubber, leather and textiles 16%, plastics 16%, paper and paperboard 13% and other less than 10%.

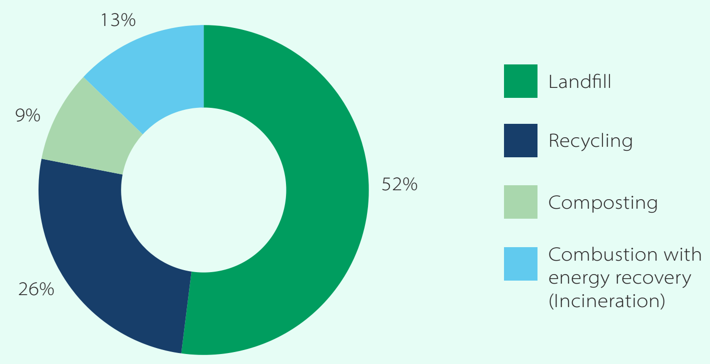


Fig 21: *"Treatment of MSW in 2015"*

The state of waste management in the US today

The US has 3,091 active landfills and over 10,000 old municipal landfills, according the EPA.

A 2019 report published by strategic risk consultancy Verisk Maplecroft titled "US tops the list of countries fuelling the waste crisis,"[28] asserts "America's thirst for consumption is not matched by its appetite for recycling." New data reveals the country is the world's top producer of waste and one the poorest of any industrialized nation for managing its trash. Just 26% of MSW is recycled, while 9% is composted. The US is the only developed nation whose waste generation outstrips its ability to recycle. Landfilling and incineration account for 65% of waste treatment.

Canada produces approximately 31m MT of MSW per year, amounting to 2.7kg of waste per person, per day. Canadians produced more waste per capita than any other country on earth[29].

28. Verisk Maplecroft: "US tops list of countries fuelling the waste crisis", 2 July 2019

29. Conference Board of Canada

Key North American market drivers: regulatory, economic, technology, social impact

(i) US regulatory drivers

In the US, the Environmental Protection Agency (EPA) regulates household, industrial and manufacturing solid and hazardous wastes under the Resource Conservation and Recovery Act of1976 (RCRA).

The RCRA, which amended the Solid Waste Disposal Act of 1965, set national goals for:

- Protecting human health and the environment from the potential hazards of waste disposal
- Conserving energy and natural resources by recycling and recovery
- Reducing the amount of waste generated
- Ensuring wastes are managed in an environmentally sound manner, including the clean-up waste that may have been spilled, leaked, or improperly disposed of

To achieve these goals, RCRA established three distinct, yet interrelated programs:

- **The Solid Waste Program** (RCRA subtitle D) encourages states to develop comprehensive plans for the management of non-hazardous industrial solid waste and municipal solid waste, sets criteria for municipal solid waste landfills and other solid waste disposal facilities, and prohibits the open dumping of solid waste
- **The Hazardous Waste Program** (RCRA subtitle C) establishes a system for controlling hazardous waste from the time it is first generated until its ultimate disposal—effectively from "cradle to grave"
- **The Underground Storage Tank Program** (RCRA subtitle I) regulates underground storage tanks containing hazardous substances and petroleum products

The RCRA was intended to be a joint federal and state enterprise. The federal program provides basic requirements that give consistency to the systems the states implement. States execute their own waste management programs, so that they can design programs that fit their needs, resources and economies[30].

In 1979, the EPA laid out design and operating conditions for sanitary landfills receiving municipal waste. This was a first step towards closing all open garbage dumps and ensuring disposal facilities posed no threats to human health and the environment.

In 1984, amendments to the RCRA, under the Federal Hazardous and Solid Waste Amendments focused on waste minimization and the phaseout of land disposal for hazardous wastes as well as corrective action for releases. Other mandates included increased enforcement authority for the EPA, more stringent hazardous waste management standards and a comprehensive underground storage tank program.

In 1988, the EPA reported that the US generated 160m tons of municipal solid waste. Of this, 131m tons (82%) was sent to 6,500 MSW landfills. The EPA found that environmental controls at these landfills were inconsistent, and they posed a threat to ground and surface water resources.

30. US EPA: "25 Years of ECRA: Building on our past to protect our future"

In 1998, the **Ocean Dumping Ban Act** was passed, prohibiting all municipal sewage sludge and industrial waste dumping into the ocean.

In 1989, as part of its **Agenda for Action,** the EPA established a goal for 25% recycling and source reduction rates by 1992.

The **Pollution Prevention Act** of 1990 required the EPA to establish an Office of Pollution Prevention and the owners and operators of manufacturing facilities to report annually on source reduction and recycling activities.

STATE LEGISLATION

Federal guidelines provided state and local governments regulatory responsibility for ensuring proper management of wastes generated from each source in their region. Programs vary considerably in their guidelines and implementation.

As of 2011, the EPA has authorized 48 US states to implement RCRA (except Alaska and Iowa). Many states follow the rules for hazardous waste management, in particular.

MUNICIPAL LEGISLATION

Municipalities oversee local recycling and waste collection. They can choose whether to contract services to private companies and how to charge for them. They may adopt numerous approaches for converting waste to energy. There is a wide variety of implementation across the country.

SAN FRANCISCO—A CITY APART

While nationwide, the US recycles just 35% of its municipal solid waste, meaning the rest (65%) is sent to landfills or incinerated, San Francisco diverts 80%[31] of its MSW away from landfills. Furthermore, the city is aiming for 100% diversion from landfills and incineration by 2020.

In 2009, San Francisco made recycling and composting a requirement for all businesses and residences. It passed the US's first mandatory composting law and banned environmentally hazardous items like carrier bags and Styrofoam.

Standard residential waste collection services include three bins across the city: (i) a 64-gallon blue recycling bin, (ii) a 32-gallon green composting bin and (iii) a 16-gallon black trash bin (for everything else).

All the city's yard waste and food scraps are converted via a composting operation to a nutrient-rich product sold as fertilizer to vineyards in wine country and to nut and other growers in the Central Valley.

31. CNBC: "How San Francisco send less trash to the landfill than any other major US city"

San Francisco has an exclusive partnership with a single waste management company, Recology, which means uniform rules and a single set of goals.

New York, by contrast, has hundreds of competing waste collection companies. It diverts just 21% of its waste from landfills and incineration. Chicago has a 10% diversion rate.

(ii) US economic drivers

NO UNIFORM LANDFILL TAX IN THE US—EXCEPT IN CALIFORNIA

The US has numerous federal laws and regulations regarding the operation of landfills, but there is no nationwide landfill tax or fee. Some states and local governments collect fees and taxes on the collection or disposal of solid waste.

Landfills in California are subject to fees and taxes levied by cities and counties. These fees are collected to recover the costs of local solid waste planning and inspection programs, programs for the collection and disposal of household hazardous wastes, and to recover some recycling and reuse program costs.

WASHINGTON D.C. SEES SIGNIFICANT FALL IN PLASTIC BAG USE WITH 5¢ CHARGE

In 2010, the District of Columbia implemented a 5¢ tax on single-use paper and plastic bags to encourage consumers to switch to reusable bags. In 2018, city officials reported plastic bag usage plummeted 50-70% since the fee took effect.

Four of the five cents charged are directed to a special fund in the D.C. Department of Energy and Environment which, amongst other activities, cleans up plastic waste from parks, rivers and other municipal areas. One cent is kept by the charging store. More than three-quarters of city businesses selling food and beverages complied with the plastic bag tax. Other cities, including New York, now have legislation pending to discourage plastic bag use. According to Forbes[32], 349 cities, counties and states in the US have now, in some way, banned or taxed plastic bag use. California and Hawaii have introduced state-wide single-use plastic bag bans.

(iii) Technological drivers

For decades, the waste industry has been a relatively low-tech business. But technology is beginning to drive changes with the hope of lowering costs and increasing efficiency[33].

- Driverless trucks may ultimately transform the industry as the technology becomes more advanced

32. Forbes https://www.forbes.com/sites/trevornace/2018/09/20/heres-a-list-of-every-city-in-the-us-to-ban-plastic-bags-will-your-city-be-next/#4ff5641f3243

33. Bank of America Merrill Lynch, "The Power To See The Road Ahead: 5 Trends in Waste Management"

- Robotics being used in materials recovery facilities
  - Traditionally, materials sorting was conducted by a group of human employees wearing gloves. In the next few years, powered by artificial intelligence (AI) and sensors, robots are predicted to be able to separate many more fractions, with much less impurities. The separation process is forecasted to become faster, more cost effective and easily adaptable to changes of input waste
- Automated sorting innovations may soon be able to keep up with increasingly stringent contamination requirements. For example, the US cleans paper to 1.5% contamination and China's limit for allowing contamination to be imported is 0.5%.
- Harnessing the power of the Internet of Things (IoT)
  - Smart technologies like fill-level and tilt-sensors could be implanted into bins and waste trucks so route managers would be alerted when they are ready to be emptied
- Companies may soon be able to provide customers with 'smart' bins that sort recycling automatically in their homes and businesses, thereby reducing inaccuracy and human reluctance to separate recyclables irreverent. This could help waste management companies decrease sorting costs and contamination
- Dynamic routing[34] involves the use of software to optimize waste collection routes for density and fuel costs, resulting in cost savings on fuel and truck depreciation

34. "Seeking Alpha: "Waste Mega-Trends: How Will Technology Transform the Waste Sector?"

VALUE FROM WASTE - THERMO PLASTIC PELLETS FROM WIND TURBINE BLADES

Innovations are continuously created to turn waste materials into valuable commodities, as companies look to align themselves with a circular economy and move away from a linear model.

One such inventive US company is Global Fiberglass Solutions (GFS). GFS recycles decommissioned wind turbine blades and other fiberglass products into thermoplastic pellets. These can be used in injection molding and extrusion manufacturing processes. Such pellets can be used to make panels for construction, pallets for road and railway applications, to name a few. This diverts fiberglass waste away from landfills or incineration into a tailored product with several applications.

(iv) Social / impact drivers

Plastics – *banning single-use plastics in the US & Canada*

There is no current federal ban on single-use plastics in the US, which makes bans a bit complicated as a whole, however certain cities and states are pushing for their own laws.

Jurisdictions across the US have instituted bans and fees on various types of plastics, such as bags, carryout containers, polystyrene (Styrofoam), and straws. States have also enacted restrictions to prevent future plastic bans. Nation-wide, there is currently a ban on the use of microbeads[35].

Four states, including California and New York, have passed state-wide bans, and Hawaii has a de facto ban. Several state legislatures, including those in Oklahoma, Tennessee and North Dakota, have taken steps to stop plastics bans with pre-emptive laws prohibiting cities from passing their own restrictions, according to the National Conference of State Legislatures[36].

In June 2019, Canada's Prime Minister, Justin Trudeau, announced Canada will aim to ban single-use plastics by 2021. The ban will likely include plastic bags, straws, cutlery, plates, and stir sticks. Canada will also establish "targets" for companies that manufacture or sell plastics to be responsible for their plastic waste[37].

This initiative is modeled on similar legislation passed last year by the European Union and other nations.

Recycling – *room for improvement for the US*

The EPA has declared they are thinking beyond waste, and actively brainstorming a systematic approach that will provide a transition from waste management to sustainable materials management (SMM).

Recycle Across America reports when US recycling levels reach 75%, it will be the environmental and CO_2 equivalent of discarding 55 million vehicles from the roads each year, plus an accumulation of 1.5 million new jobs across the country.

The most critical issue in the US is the sorting and management of discarded plastic. In order to resolve this issue, the public needs to be informed on how to sort and recycle materials[38].

35. "See the Complicated Landscape of plastic bans in the U.S."

36. "Plastic Bans: What You Need to Know."

37. "Canada Announces a Plan to Ban Single-Use Plastics by 2021."

38. "American Recycling Facts: Comparing the U.S. to Other Countries."

Section 3

Overview of Waste-to-Value Targets

Waste-to-Value is the process of converting waste that is not usually re-usable or recyclable and might otherwise be destined for landfills into useful products or resources with monetary value.

Target project types and examples include:

- Waste-to-**Energy**
  - Producing electricity, heat or combined heat and power (CHP) from biomass, refuse derived fuel (RDF), solid recovered fuel (SRF) and incineration
- Waste-to-**Fuels**
  - Producing solid fuels such as wood pellets, RDF, SRF, and gases from anaerobic digestion and landfill gas
- Waste-to-**Materials**
  - Producing bio-thermoplastics, sustainable yarn for textiles, bio-chemicals, bio-jet fuel, fertilizer and compost

Of critical importance for each project is the need for:

- Consistently available supply of suitable feedstock
- Commercially proven conversion technology
- Calculable outputs and off-take customers and contracts

Waste-to-energy

Waste-to-energy is the process of generating electricity, heat or combined heat and power (CHP) from the primary treatment of waste. Many waste-to-energy processes typically generate electricity and/or heat directly through combustion.

(i) Biomass-to-energy [electricity, heat or combined heat and power (CHP)]

Biomass is considered an import source of renewable energy. Biomass can be used as a feedstock to generate electrical power, heat and/or steam, or combined heat and power (CHP).

Biomass waste-to-energy plants have the advantage of producing a base load and/or 'dispatchable' source of renewable energy, meaning it is either always on or controllable and available when needed, unlike wind and solar power generation, which are intermittent sources of renewable energy.

INPUTS:

For commercial biomass-to-energy plants, the most common feedstocks are wood pellets or wood chips. Wood pellets have significant advantages over other biomass feed stocks, including: (i) high energy density, i.e. more power/heat per MT of input material (ii) low and consistent moisture content (iii) high bulk density (more energy per cubic meter - better for transporting) and (iv) low ash content (less residual waste to deal with).

Fig 22: *"Wood pellets"*

Other biomass feedstocks include forestry and agricultural residuals such as forestry thinnings, biomass briquettes (usually made from compressed straw), and a variety of crop residues like straw, corn and sugarcane bagasse. Some biomass materials are purpose-grown as 'energy crops.' Examples include short rotation coppice such as willow, poplar and grasses, reed canary grass and switch grass.

TECHNOLOGY/PROCESS:

Most biomass power plants use direct-fired combustion technology. The technology is mature and, assuming it is well maintained, can be considered low risk.

PRODUCING POWER/HEAT:

The biomass feedstock (e.g. wood pellets) is fed into a combustor or furnace, where the biomass is burned with excess air, it heats water in a boiler to create steam. Steam from the boiler is then expanded through a turbine, which spins to run a generator and produce electricity.

. https://www.powervamp.com/news/ince-biomass-energy-plant/

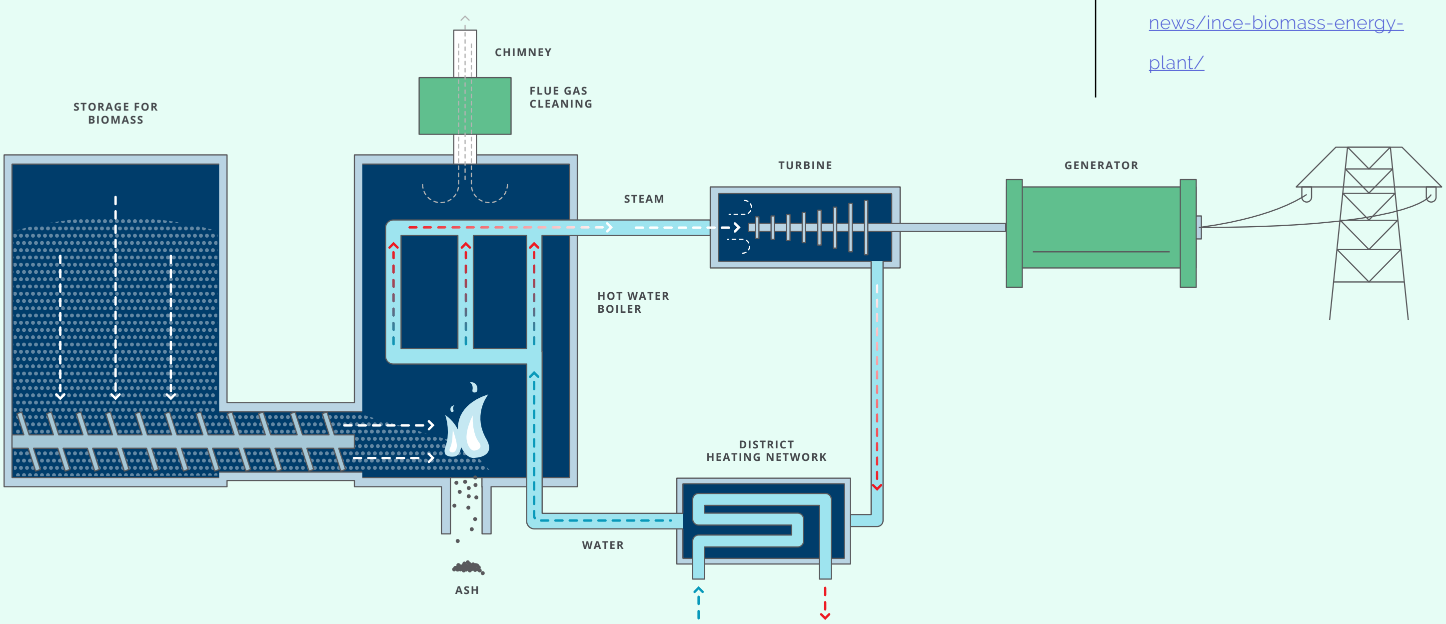


Fig 23: "Biomass-fired power plant operation"

There are two principal types of biomass generation combustion systems:

1) **Fixed-bed system**
The biomass fuel is delivered onto a grate where it reacts with oxygen in the air. This is an exothermic reaction (releasing energy) which produces extremely hot gases and generates steam in the heat exchange section of the boiler.

2) **Fluidized-bed system**
The biomass fuel is burned in a hot bed of suspended, incombustible particles, such as sand. This usually produces a more complete carbon conversion, resulting in reduced emissions and improved system efficiency.

EMISSIONS:

Biomass power and heat generation are considered CO_2-neutral in the sense that when biomass burns, it releases only the quantity of CO_2 that the biomass feedstock absorbed during growth.

Other emissions include unburned hydrocarbons, nitrous oxides and sulfur dioxide. To limit emissions, a variety of technologies may be employed. They might include a cyclone, or multi-cyclone, bag house, or electrostatic precipitator. The primary function of these technologies is to control particulate matter. Additional emissions-control technology may also be required dependent on location and regulatory requirements.

In February 2019, Drax Power Station, a converted-coal-fired power plant in North Yorkshire England, installed a Bio-Energy Carbon Capture and Storage (BECCS) technology demonstration pilot. The project, if scaled up, is believed to have the potential to enable Drax to become the world's first 'negative emissions' power station.

OUTPUTS:

Biomass plants can produce power, heat or combined heat and power (CHP). The electricity can either be exported to the electricity grid or used to provide power to local industrial facilities. Heat can be exported to a district-heating network, where local infrastructure exists. Steam can be used by local industrial facilities.

The power output from industrial biomass power plants can range from small, e.g. 1-2 MW, to very large. Drax Power Station is the world's largest biomass power plant, with a current biomass power output capacity of 2,929 MW[39].

In 2015, biomass produced 6% of all electrical power generation amongst EU-28 countries (19% of all renewable energy generation). Biomass provided 16% of all energy for heating and cooling in the EU in the same year (88% of all renewable heating and cooling)[40].

39. https://www.drax.com/about-us/our-businesses/

40. http://www.europeanbioenergyday.eu/bioenergy-facts/bioenergy-in-europe/what-is-the-eu28-bioenergy-consumption/

In the US, biomass produced around 2% of electricity in 2016, according to the US Energy Information Administration.

(ii) Refuse Derived Fuel (RDF) to energy (electricity, heat or CHP)

RDF is a fuel produced from selected waste streams— usually those that cannot be re-used or recycled—including MSW, industrial waste and commercial waste.

INPUTS:

RDF largely consists of combustible components of wastes where there is recoverable calorific value, such as non-recyclable plastics, paper, cardboard and other corrugated materials. It sometimes contains rubber products, such as shredded tires.

RDF is made by first separating out fractions that can be recycled from mixed waste streams, such as ferrous and non-ferrous metals and glass. Other 'foreign' items are then removed, e.g. stones and non-calorific items. The remaining material is shredded into a uniform grain or sized and dried to low moisture levels (typically around 10%).

Fig 24: *"Baled RDF"*

TECHNOLOGY:

RDF is commonly used as a substitute for a portion of fossil fuels (e.g. coal) in coal-fired power stations, cement kilns or iron and steel furnaces. It is also used in CHP (incineration) plants.

OUTPUTS, USES AND APPLICATIONS:

RDF is seen as a useful fuel, composed of wastes that would otherwise likely be sent to landfills. Given the fact that, if prepared well, RDF can have a calorific value close to that of coal, it can be used as a substitute for a portion of coal used in existing energy generation plants. RDF can provide for a significant improvement in air emissions quality as compared to coal[41].

RDF can be used in a variety of ways:

- To produce electricity and/or heat alongside coal in coal-fired power plants
- In Europe, it is commonly used in cement kilns, replacing a portion of coal where the strict standards of the Waste Incineration Directive are met (e.g. in Germany, RDF has replaced approximately 62% of coal as an energy source in the cement industry)
- In combined heat and power facilities (incinerators)
- In plasma arc gasification modules (a thermal process for conversion of organic matter to a synthetic gas)
- In pyrolysis plants (a process involving 'thermal cracking' used to break down large molecules into smaller molecules to produce fuel oil from waste plastic)

(iii) Incineration: Waste-to-Energy (electricity, heat or CHP)

Incineration is a high temperature waste treatment process that converts municipal, commercial, industrial and hazardous wastes unsuitable for re-use or recycling into heat, ash, and flue gas. Incinerators prevent waste materials that may be too polluted or poor for further recycling from going to landfills, while generating energy in the form of electricity, heat and steam.

Incineration plants provide base-load reliable electricity around the clock. Such plants can also supply district heating networks with a reliable and efficient source of heating and hot water where suitable infrastructure exists.

41. Pirelli Ambiente S.p.A. presentation "Existing plants, waste-to-energy and CO_2 reduction a sustainable equation"

In the EU, the Waste Framework Directive establishes a clear hierarchy for how waste materials are handled. It puts waste prevention, reuse and recycling first. For materials that cannot be reused or recycled, the next best option is waste recovery through incineration, followed by landfilling as a last resort.

INPUTS:

Commonly incinerated types of waste include plastics, packaging materials, polystyrene, cardboard, wood, construction and other industrial wastes, rubber products, cloth, oily rags, oil filters, paint scraping, food waste, sludge oil, waste lubrication oil, nappies and female hygiene products. Due to the high operating temperature, where pathogens and toxins can be destroyed, incineration is also ideal for treating clinical and other types of hazardous wastes.

TECHNOLOGY:

There several types of incinerator technology, including:

- **Moving Grate:** used for treating MSW. Waste moves through the combustion chamber across a series of inclined moving grate bars, allowing for continuous processing and generation of heat and power
- **Fixed Grate:** a slightly dated type of incinerator comprised of a brick-lined cell and a fixed metal grate over a lower ash pit. An opening in the top or side is used for loading the waste and another side opening is used for removing incombustible solids
- **Rotary Kiln:** Commonly used for incineration of hazardous wastes, chemical wastes and dry sewage waste, the rotary kiln comprises two chambers. In the primary chamber, movement of the cylinder on its axis facilitates rotation of the waste, where it is converted into gases through volatilization (vaporisation), destructive distillation and partial combustion reactions. A secondary chamber is necessary to complete gas phase combustion
- **Fluidized Bed:** A strong airflow is forced through a sand bed where a mixture of sand and pre-treated waste is kept suspended on pumped air. The waste and sand are violently mixed and agitated, allowing all the mass of the waste and sand to be fully circulated in the furnace

. https://www.oxfordmail.co.uk/news/11286048.a-burning-issue-that-will-never-go-away/

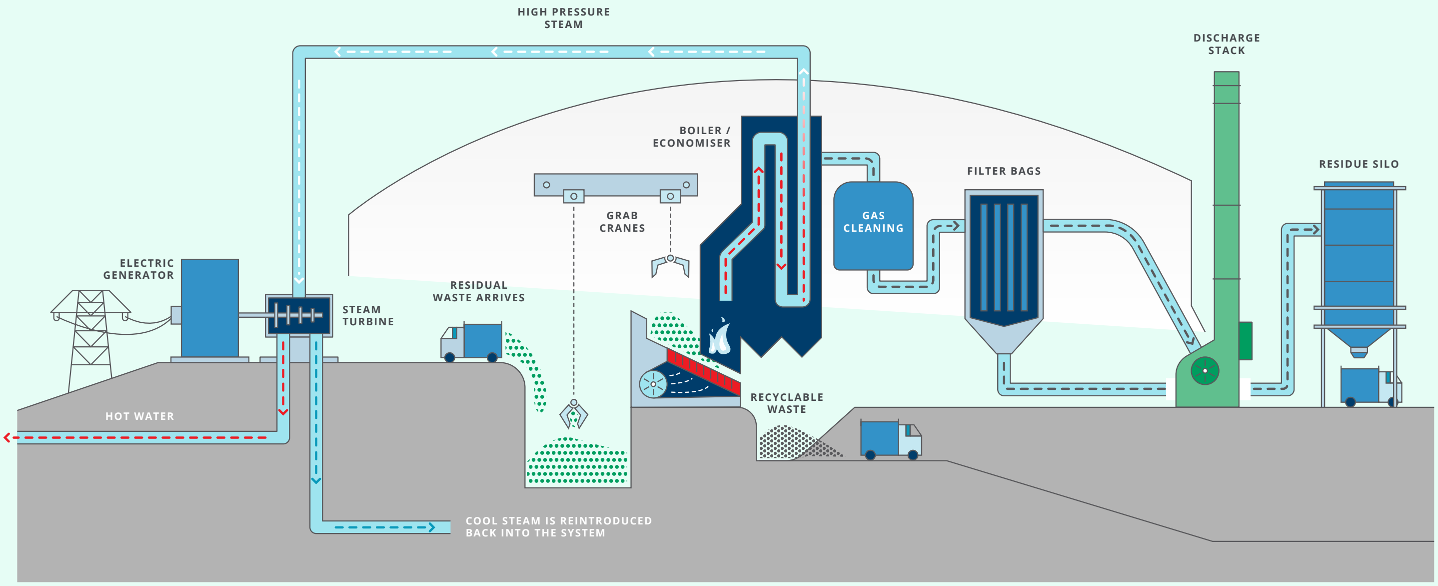


Fig 25: "How the Ardley Incinerator Works"

1) Waste is tipped from refuse vehicles into a reception holding area.

2) Waste is mixed, lifted by a grabber and dropped into a hopper.

3) The waste material is dumped onto a moving grate and fed into a furnace at a controlled rate for burning at high temperatures, commonly between 850°C and 1,200°C. An adequate air supply is maintained through the injection of air into the combustion chamber, ensuring optimum and complete combustion.

4) Steam is superheated to drive a turbine in the power plant and generate electricity.

5) A significant part of the plant is devoted to the cleaning of exhaust gases. Dry, ground-hydrated lime is used to remove acid gases. Activated carbon is used to absorb heavy metals, dioxins furans and volatile organic compounds (VOCs). Clean flue gases, steam and carbon dioxide then exit and are discharged through the stack.

6) Telemetry linked to pollution prevention and control systems monitor emissions from the plant.

7) Remaining dust and reaction products are collected in very fine filters. The residues are gathered by screw conveyors and directed to a residue silo. The silo is designed to safely discard the residue through a loading chute, into trucks, and off to be recycled or disposed of in a licensed facility.

8) Metals are collected and recycled.

9) Bottom ash is removed and fully recycled into sand or aggregate products for construction or road building.

OUTPUTS:

Typically, 500 kWh of electricity can be generated from one tonne of waste (20-22% efficiency), although if a CHP is incorporated, and the thermal energy is utilized, combined efficiencies of up to 85% are possible[42].

Value outputs from incineration waste-to-energy plants include:

- Electricity
- Heat
- Steam
- Metals (extracted from the bottom ash and recycled)
- Incinerator Bottom Ash (IBA), which can be processed to create a sustainable source of aggregates for use in several construction applications, including road pavements, concrete, bituminous mixtures and surface treatments for roads and airfields

ENVIRONMENTAL CONCERNS:

Historically, there have been concerns about emissions from incineration facilities, in the absence of effective controls. Fly ash, heavy metals, dioxins and furans may be present in the waste gases, water or ash.

In Europe, modern incineration plants achieve high standards of emission control. Incinerator emissions are closely controlled and monitored. The Waste Incineration Directive of 2000 aims to minimize the impact of incineration on the environment and human health. The EU's Industrial Emissions Directive from 2014 further imposes strict standards.

In the US, incinerator emissions are imposed at federal, state and local levels, which can vary from place to place[43]. Regulations arise under the Clean Air Act, Clean Water Act, Toxic Substances Control Act and other policies. Direct federal regulation and oversight is the responsibility of the Environmental Protection Agency.

INCINERATION USE ON THE RISE:

Incinerators are popular in countries where land is a scarce resource. Several European countries rely heavily on incineration, including Germany, France, Holland and Luxemburg. In total, the EU has more than 400 incinerators in 23 countries. Approximately 28% of the EU MSW was incinerated in 2017, up from 15% 20 years earlier[44]. By contrast, the US only has 86 incinerators[45]. Around 12% of the total US MSW stream is incinerated.

42. https://www.ciwm.co.uk/ciwm/knowledge/incineration.aspx
43. The National Academies of Science Engineering & Medicine. Waste Incineration and Public Health
44. https://ec.europa.eu/eurostat/statistics-explained/images/5/5d/Municipal_waste_landfilled%2C_incinerated%2C_recycled_and_composted%2C_EU-28%2C_1995-2017.png
45. https://theconversation.com/garbage-in-garbage-out-incinerating-trash-is-not-an-effective-way-to-protect-the-climate-or-reduce-waste-84182

The UK had 44 waste incinerators in 2018 burning a combined 10.9m MT of waste—42% of the overall rubbish disposal in England[46]. The number is set to more than double over the next decade. Sixteen incinerators are currently under construction and a further 45 have been approved. Growth in the number of incinerators is driven by a combination of increases in landfill taxes and the impact of China and several other Asian countries, having banned the import of paper and plastic waste from around the world, including the UK.

Large quantities of British waste were previously sent to China and elsewhere in Asia. Much of this— which comprises materials that cannot currently be recycled—is likely to end up in an incinerator. Uncertainty over post Brexit, which some fear may ultimately shut off Europe as a waste export destination, is also a factor.

46. https://inews.co.uk/news/environment/waste-incinerators-double-burning-rubbish-air-pollution-uk

47. http://www.bioenergyadvice.com/facts/bio-fuel-units-of-measurement-energy-values-and-conversion-factors/

Waste-to-Fuels

(i) Solid fuels

WASTE-TO-WOOD PELLETS (AS A SOLID FUEL)

Wood pellets are a preferred fuel source for the generation of renewable energy from biomass. Biomass is a relatively clean renewable energy source. A principal advantage of biomass energy is that it produces a smaller amount of harmful greenhouse gases than fossil fuel alternatives, especially compared with coal.

For commercial power and heat generation, wood pellets are preferable as compared to other biomass feedstocks, i.e. wood chips.

Wood pellets have:

- **Higher energy density** of 2,900-3,900 kWh/m^3, compared with 700-900 kWh/m^3 for wood chips[47]
- **Lower moisture content**—commonly 8-10%. As a result, in the pellet production process, this moisture content is relatively stable. The moisture content of high-quality wood chips is around 25%-30%, and even greater when the quality is lower. However, the moisture content of wood chips can vary greatly depending on weather and storage conditions
- **>2x the bulk density**, making it better for transportation, at 600-650 kg/m^3, compared with 250-320 kg/M^3 for wood chips
- **Lower ash content**, at 0.5 wt.%, compared with a 0.5-2.0 wt.% for wood chips

. https://www.wbdg.org/resources/biomass-electricity-generation

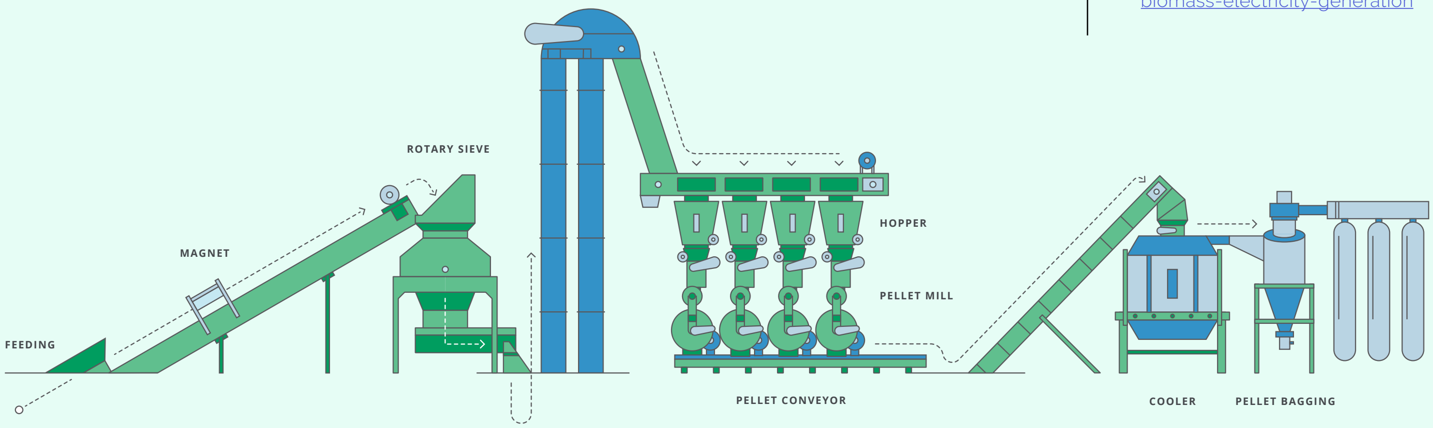


Fig 26: "Wood Pellet Manufacturing Plant"

THE PROCESS OF WOOD PELLET MANUFACTURING[48]:

The technology for wood pellet manufacturing is relatively mature.

Wood pellets are most commonly composed of compacted sawdust. Sources of wood fiber predominantly originate from forestry operations and wood processing industries, including:

- Forest thinnings
- Tops and branches from logging operations
- In some cases, whole logs from sustainable forestry operations
- Sawdust, offcuts, trims and shavings from wood processing industries like sawmills and manufactures of plywood, wood panels, furniture and flooring

1) **Raw material preparation/chipping**
A woodchipper with multiple blades spins and cuts logs, branches and other wood fiber sources into small wood chips, roughly 10mm long and 3mm thick.

2) **Drying and sieving**
The chips are dried to a moisture content of 8-12%, usually in a rotary drum dryer. Chips are sieved in a de-stoner to separate contaminants, including stones, sand, soil, bark and other residues, before being subjected to a magnetic separator that removes any metal particles.

48. Renewable Energy World: Wood Pellet Manufacturing Steps https://www.renewableenergyworld.com/ugc/articles/2016/05/how-to-make-wood-pellets--wood-pellet-manufacture-steps.html https://www.drax.com/technology/this-is-how-you-make-a-biomass-wood-pellet/

3) **Hammering, followed by intense pressure to make pellets**
Wood chips are fed into a hammer mill, where they are pulverized into a fine, powdery, sawdust-like substance, before being fed into a pellet mill. The wood fiber is pressed under intense pressure through a grate featuring several small holes. This pressure heats up the wood fiber, helping bind it together as it passes through the holes in the metal ring dye, forming the compressed wood pellets. The pellets are then moved to storage where they cool down and harden.

Fig 27: *"Ring Die Hole"*

OUTLOOK FOR WOOD PELLET MARKET DEMAND AND MANUFACTURING:

Wood pellets are seeing significant growth in demand, as illustrated in the following graph. Their adoption in Europe is particularly strong, as pellets are viewed as a positive alternative to coal in a continent hoping to meet climate change goals with the rapid closure of coal-fired power plants in favor of renewable energy power generation.

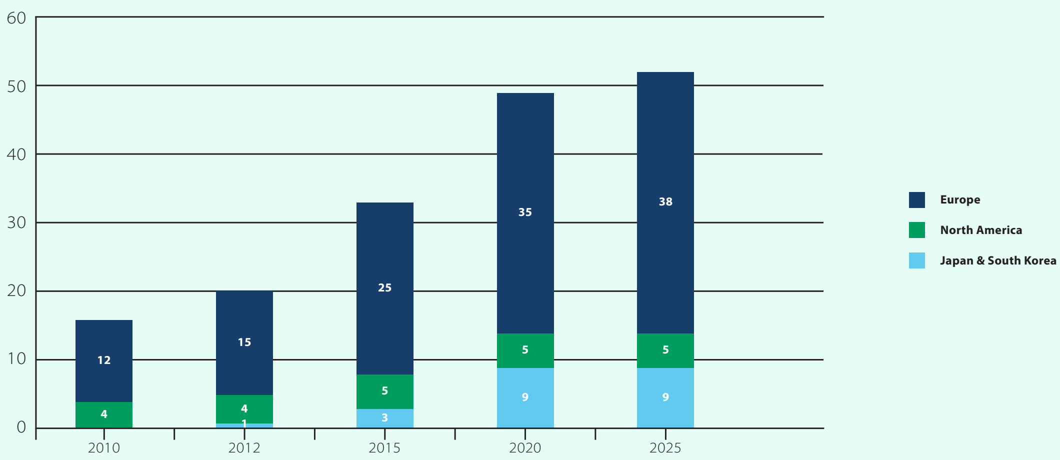


Fig28: *"Global wood pellet market 2010 - 2025"*

. https://www.statista.com/statistics/243910/global-wood-pellet-consumption-outlook/

Europe is expected to remain an important and growing market for wood pellets, with demand anticipated to grow by 52%, from 25m MT in 2015 to more than 38m MT by 2025[49]. While the EU produces about half of the world's wood pellets, its consumption accounts for around 75%.

The UK is currently Europe's largest single consumer market by far (close to 7m MT in 2016), almost all of it imported. This is partly a function of the UK having closed most of its coal-fired power stations. Today, coal accounts for only 5% of the UK's electricity generation mix, down from 40% in 2012. Its remaining seven coal-fired power stations are set to close by 2025.

Denmark, Italy, Germany and Sweden are also major wood pellet consumers. Although western Europe is ranked amongst the biggest wood pellet producing regions worldwide, a large part of Europe's growing wood pellet demand is likely to be met by imports from the US and Canada. US wood pellet exports to the UK grew from c. 0.75m MT in 2012 to just over 4m MT in 2017[50].

Companies like Drax in the UK and RWE in Germany account for a considerable amount of industrial wood pellet consumption.

WASTE-TO-REFUSE DERIVED FUEL (RDF) (AS A SOLID FUEL)

Refuse Derived Fuel (RDF) is a solid fuel produced from residual MSW, industrial waste or commercial waste (including pre-consumer wastes like materials used in manufacturing and bulk packaging of products). RDF is usually made from wastes that cannot be re-used or recycled.

RDF principally consists of combustible components of waste streams, which may include non-recyclable plastics (not PVC), paper, cardboard, labels and other corrugated materials. It can sometimes include rubber products such as (shredded) tires.

49. IEA Bioenergy: "Global Wood Pellet Industry and Trade Study, 2017"

50. https://www.pri.org/stories/2018-06-20/uk-s-move-away-coal-means-they-re-burning-wood-us

PROCESS OF PRODUCING RDF:

1) **Shredding:** using a shredder, a mixed waste stream is shredded to a consistent size.

2) **Extraction of fines:** if there is a substantial amount of organic material, it must be removed before further processing.

3) **Preparation of RDF fraction:** readily separable recyclables are removed (e.g. metals and glass) using magnets and mechanical screening.

4) **Post-shredding:** high-calorific fraction is post-shredded to the grain size specified by the customer.

5) **Additional processing steps** can be applied to achieve the desired quality in terms of chlorine, metal or ash content for various applications.

There is no universal or industry-wide specification for RDF. The customer often dictates the RDF fuel specifications. The fuel can be tailored for attributes such as calorific value, grain size and ash content. RDF can also be made into pellets.

***Fig 29:** "RDF Pellets"*

END MARKETS FOR RDF:

- Coal fired power plants
  - RDF can be used to substitute a portion of the coal used to produce electricity
- Cement plants
  - In Europe, RDF is commonly used in the cement industry, replacing a portion of coal in the cement kiln to reduce overall emissions
- Multi-fuel (waste-derived fuels) energy plants
- Plasma arc gasification modules
- Pyrolysis plants

RDF PRODUCERS:

In the UK, waste management company Biffa is one of the largest producers of RDF. It delivers around 2,000 MT of RDF to energy recovery facilities in the UK, Netherlands, Germany and Sweden. For example, Biffa delivers almost 1,000 MT of RDF daily to a multi-fuel energy recovery facility in Ferrybridge, West Yorkshire.

Since 2010, the UK has exported RDF (and SRF) to several European countries, notably Germany, Netherlands and Scandinavian countries. Exports peaked at around 3.2m MT in 2017. This has enabled UK waste producers to divert residual waste from landfills and convert it to energy at UK and European plants.

WASTE-TO-SOLID RECOVERED FUEL (SRF) (as a solid fuel)

Solid Recovered Fuel (SRF) is a more refined, higher specification fuel as compared to Refuse Derived Fuel (RDF). While RDF has no official definition or specification, Solid Recovered Fuel (SRF) has a defined European standard: CENTC 343. SRF is produced in accordance with European Standard EN15359, from waste streams such as MSW, construction and demolition waste and industrial waste. However, it cannot include hazardous wastes.

The main requirement is that the producer specifies and classifies its SRF by detailing[51]:

- No hazardous waste content
- Net calorific value
- Chlorine content
- Mercury content
- A declaration of conformity to requirements of EN15359

51. European Recovered Fuel Organization (EFRO) "Standardisation of SRF"

PRODUCTION OF SRF:

SRF is produced by passing the input material through a series of shredders, screens, air classifiers, density separators and magnets.

Inert materials, recyclable plastics and metals are extracted, leaving a mix of mainly non-recyclable paper, card, wood, textiles and plastic. Although a small portion of these materials can be recycled, their quality is compromised once they enter the residual waste stream, and recovering energy from those materials is the best current environmental option.

THE MARKET FOR SRF:

In Europe, approximately 49% of SRF is used in CHP plants, 40% in cement kilns, 8% in co-combustion and 3% in MSW incineration and gasification plants.

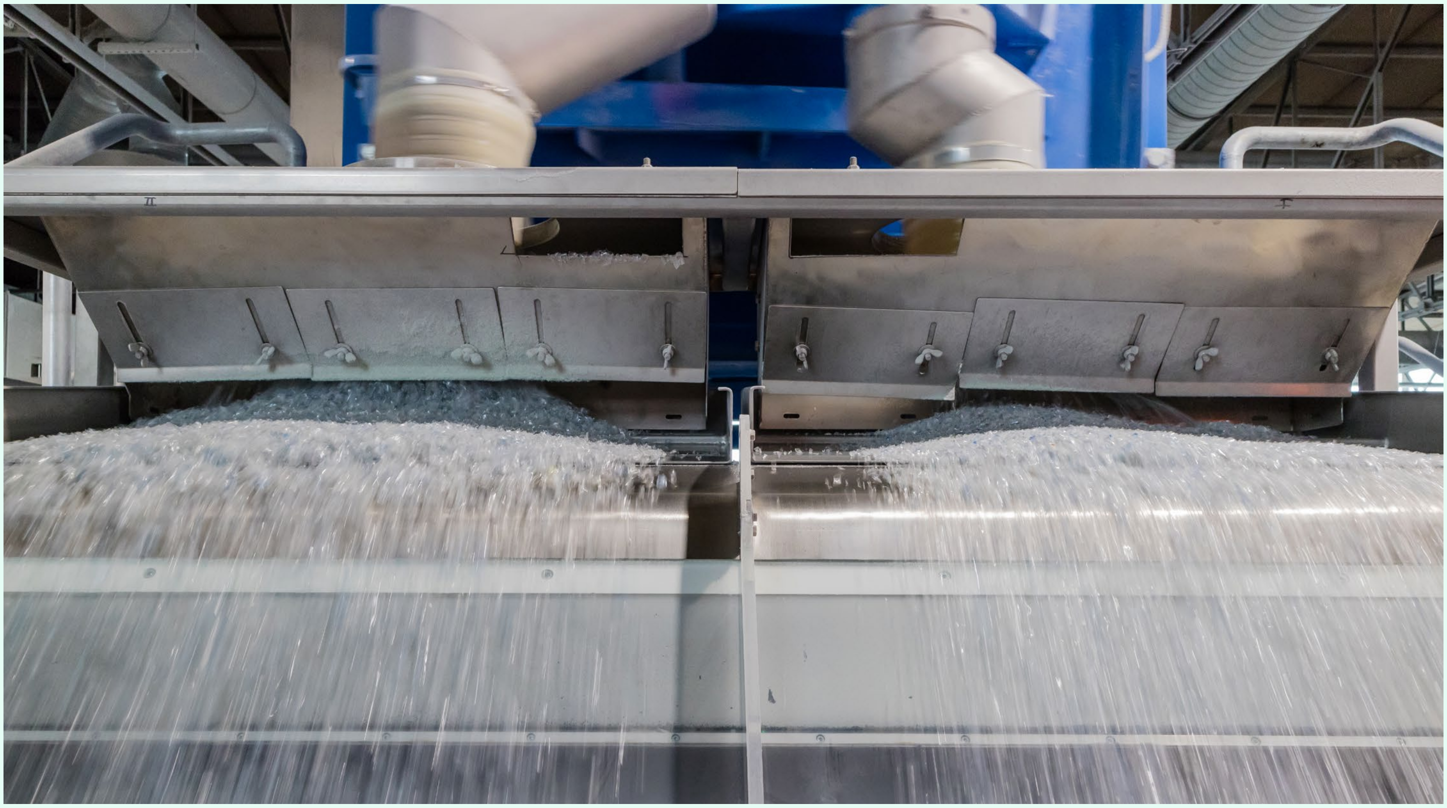


Fig 30: *"SRF"*

(ii) Gases

ANAEROBIC DIGESTION (AD)

Anaerobic digestion is a process by which organic matter, such as food waste, animal waste and sewage sludge, is broken down by microorganisms to produce biogas and bio-fertilizer.

Anaerobic digestion is widely used as a source of renewable energy. The process produces a biogas consisting of methane (CH_4), carbon dioxide (CO_2) and traces of other 'contaminant' gases. The biogas, when cleaned to remove CO_2 and other contaminants, can be used directly as a fuel if combined with heat and power gas engines to produce electricity and heat, compressed to produce a liquid fuel for vehicles, or upgraded to a natural gas-quality biomethane. In addition, a nutrient-rich 'digestate,' left behind as a residual material from the process, can be used as a fertilizer.

INPUTS:

Almost any organic material can be processed as a feedstock for anaerobic digestion. However, to maximize biogas production (to produce renewable energy), the more putrescible (liable to decay/digestion), the higher the gas yields possible.

Feedstocks include biodegradable organic wastes like leftover food, wastepaper, grass clippings, sewage and animal wastes. Specially grown energy crops (e.g. silage and corn) can also be added. Wood and bark are not generally used as feedstock, as they take a long time to break down.

TECHNOLOGY/PROCESS:

Anaerobic digestion is a natural process in which microorganisms break down organic materials (e.g. waste food, or other material made from plants and animals) in a closed space without oxygen. The system whereby anaerobic digestion occurs is called a digester.

Fig 31: *"Anaerobic Digestion Plant"*

Several microorganisms promote chemical processes that convert biomass material to biogas in the absence of oxygen, including acid-forming bacteria (acetogens) and methane forming archaea (methanogens). Most of the chemical energy contained in the organic feedstock is released as methane.

As populations of anaerobic microorganisms can typically take a significant period to establish themselves, a digester is commonly "seeded" with materials containing existing microorganism populations.

The residence time in a digester varies with the amount and type of feedstock material and the configuration of the digestion system. In a typical 2-stage mesophilic design (where organisms can flourish at moderate temperatures, commonly between 20˚C and 45˚C), residence time varies between 15 and 40 days. In a single-stage thermophilic design (where organisms thrive at relatively high temperatures, between 41˚C and 122˚C) residence time takes around 14 days.

The length of time required for anaerobic digestion depends on the chemical complexity of the material. Material rich in easily digestible sugars breaks down quickly, whereas lignocellulose material (dry plant matter) can take much longer.

OUTPUTS:

The outputs of anaerobic digestion are:

- Biogas - mostly methane (CH_4)
- Carbon dioxide (CO_2)
- Small amounts of water vapor and other gases

The biogas is commonly cleaned to remove carbon dioxide, water vapor and other trace contaminants. Removing these compounds increases the energy value of the biogas.

The biogas can be used to produce:

- Electricity and heat by powering an engine (e.g. a Jenbacker gas engine)
- Heating fuel for boilers or furnaces
- Transportation fuel to run vehicles [as compressed natural gas (CNG) or liquefied natural gas (LNG)]
- Gas to supply homes and businesses through the natural gas pipeline
- Digestate (fertilizer)

The material left after anaerobic digestion happens is called 'digestate.' This is a wet mixture usually separated into a solid and a liquid. Digestate is rich in nutrients and can be made into other products including:

- Fertilizer
- Bedding for livestock
- Soil amendments

Digestate can be applied directly to the land to improve soil characteristics and spur plant growth. It can also be refined into products that are bagged and sold in stores. Through further processing of digestate, nitrogen and phosphorus can be recovered to create concentrated nutrient products, such as struvite (magnesium-ammonia phosphate) and ammonium sulphate fertilizers.

Landfill gas

Landfills are specially designed facilities where MSW that cannot be reused, recycled, incinerated or composted is buried. Landfills are designed with a layer of clay-like soil at the bottom to prevent leachates (environmentally harmful liquids from the waste) from leaking down through the soil into the water table. They are composed of layers of soil and refuse with a synthetic lining, usually made of plastic, in between each layer.

. https://landfill-gas.com/landfill-gas-collection-systems-definition

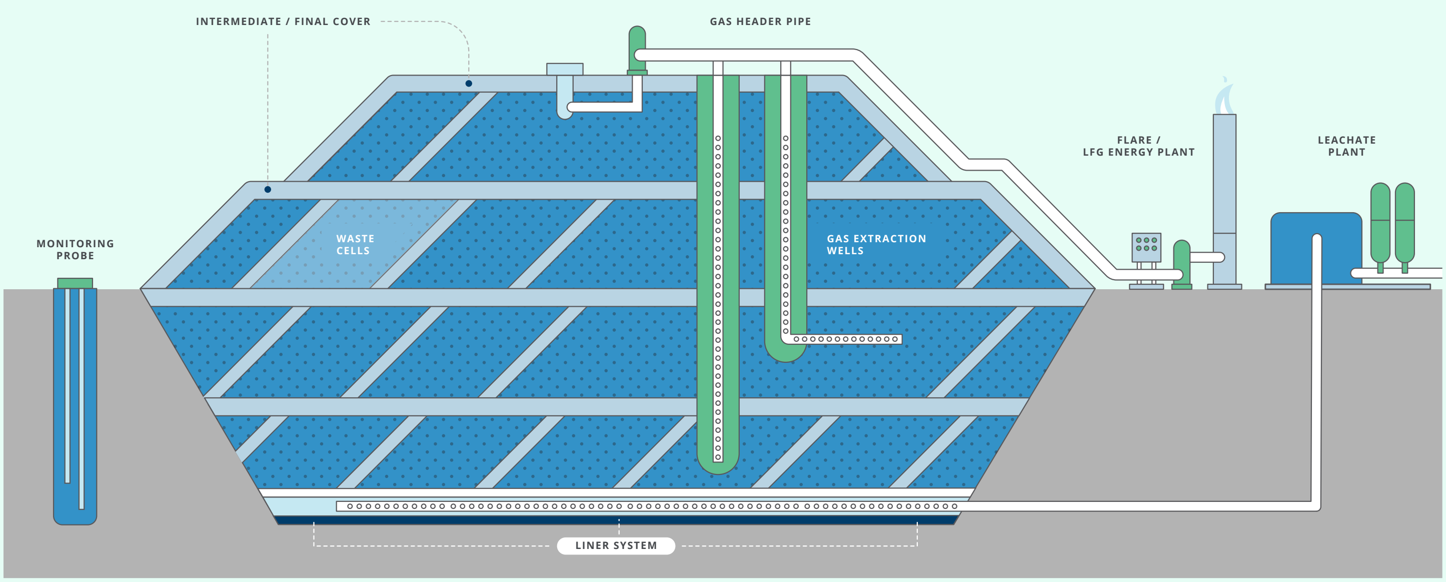


Fig 32: "Schematic of a Landfill"

INPUTS:

Items that go into landfills typically include the following:

- Natural and synthetic rubber (but not tires)
- Plastics (bags, wrappers, films, plastic items mixed with metals or rubber, Polystyrene, sponges, dental floss, food wrappers, cigarette filters)
- Animal feces and sanitary products (cat litter and bagged animal feces, nappies, female sanitary products)
- Organics (biodegradable packing and foam materials, wood, textiles)
- Ceramic dishware and glassware
- Waxed cardboard
- Pens and pencils
- Glass mirrors and windows

- Lined paper products (with foil or plastic)
- Incandescent light bulbs

HOW IS LANDFILL GAS PRODUCED?

Landfill gases are produced as a result of three processes:

- Evaporation of volatile organic compounds, such as solvents
- Chemical reactions between waste components
- Microbial action, especially by methanogenesis (organisms that produce methane)

The dominant process in landfills is microbial action—where anaerobic bacteria decompose organic wastes to produce biogas, consisting of methane and carbon dioxide, together with traces of other compounds. Typically, methane and CO_2 begin being produced around six months after landfill material is deposited. Gas output reaches a maximum output after about 20 years, and then declines over the course of decades.

TECHNOLOGY/PROCESS: HOW IS LANDFILL GAS COLLECTED AND EXTRACTED?

Landfill gas collection is achieved through installation of vertical or horizontal wells in the waste mass, with approximately one well per acre of landfill surface. Gas extraction from closed landfills (those that no longer take fresh waste and are sealed on top) yield higher quantities of gas than those from open landfills (those still taking fresh waste).

Gas is extracted and piped to a collection header, typically by using a blower to extract the gas from the collection wells. The main collection header is also commonly connected to a leachate collection system to gather condensate forming in the pipes.

Extracted gas must be treated to remove impurities, condensate and particulates. If the gas is to be used for electricity production, it will typically go through a two-stage process. Primary processing removes moisture and particulates and cools and compresses the gas. Secondary processing employs multiple clean-up methods. In addition to carbon dioxide, nitrogen and oxygen, sulfur compounds and siloxanes must be removed.

OUTPUTS AND USES:

Landfill gas commonly comprises around 55-60% methane (CH_4), around 40-45% carbon dioxide (CO_2), with trace amounts (less than one percent) of nitrogen, oxygen, hydrogen sulphide, hydrogen and non-methane organic compounds (NMOCs).

The gases produced within a landfill can be used in a variety of ways to produce:

- Electricity on-site: electricity can be produced using a reciprocating piston engine, a gas turbine or micro turbine. Electricity can be generated on-site and used locally or sold to the electricity grid
- Heat through an onsite boiler, dryer, kiln or any other type of combustion system
- Pipe-line quality gas as compressed natural gas (CNG) or liquid natural gas (LNG)
- Vehicle fuel: CNG and LNG can both be used to power vehicles

In the UK, there are 414 landfill sites generating renewable electricity, with a total generating capacity of almost 900MW[52]. In 2016, the EPA reported there were between 1,900 and 2,000 landfill sites in the US. Of these, 449 are generating electricity[53].

52. Ofgem data, Renewable Energy Association.

53. https://www.epa.gov/lmop/landfill-gas-energy-project-data-and-landfill-technical-data

Fig 33: "Methane Powered Generators"

MONITORING:

Landfill gas sites require constant monitoring because the gases they contain can be hazardous and are valuable once extracted. Flame ionization detectors can be used to measure methane levels and VOC levels. Surface and subsurface monitoring is conducted, in addition to the examination of ambient air around the sites.

ENVIRONMENTAL CONSIDERATIONS:

Landfill gases have an influence on climate change, given their main components are greenhouse gases CO_2 and methane (CH_4). Methane is a far more potent greenhouse gas, having 25 times the impact of CO_2. It is estimated that 10% of all global anthropogenic (from human activity) methane emissions are from landfill[54].

Landfill gas collection and usage helps to reduce methane emissions and creates value from the gas resource as a renewable source of energy or fuel.

Waste-to-Materials

(i) Recycled products

RECYCLING OF WIND TURBINE BLADES TO THERMOPLASTIC PELLETS

Wind power has been a growing industry since the 1990s, with an estimated wind turbine lifespan of 20-30 years. As the first generation of wind turbines approach the end of their service lives, the issue of how to recycle and recover their waste materials is coming into focus. The older rotor blades are commonly constructed from glass fiber, and more modern models from carbon fiber.

At the end of 2016, there were approximately 314,000 wind turbines operating around the world[55]. According to utility company Veolia, up to 50,000 MT of rotor blade waste materials are expected to arrive at waste reception centers between 2018-2020[56].

Innovations are being developed to recycle fiberglass from wind turbine blades and other sources. Veolia has developed a rotor blade saw, which can cut blades up into small pieces on-site, making them easier to transport to reprocessing facilities. It can then crush and mix the fiberglass with other components to become a high-quality solid fuel (RDF) for the cement industry.

54. World Bank "Building on success: new ways to keep methane out of the atmosphere"

55. Global Wind Energy Council (GWEC)

56. Veolia, # LivingCircular blog "How can wind turbine blades be recycled", June 2018

Fig 34: *"End-of-life Wind Turbine Blades Awaiting Recycling"*

Global Fiberglass Solutions (GFS), an innovative US company based out of Irving, Texas, has developed and commercialized a process to turn end-of-life wind turbine blades into thermoplastic fiberglass pellets, which can be used in injection molding and extrusion manufacturing processes. These pellets can be made-to-order based on the requirements of the customer's own manufacturing process.

Business and consumer interest in these types of materials and the products they produce is at an all-time high and expected to grow as the global economy shifts from a liner economy model to a circular economy model, where valuable resources are re-purposed to create environmentally sustainable products.

Types of products manufactured with these thermoplastic glass fire pellets to-date include decking boards, warehouse pallets and parking bollards. The company expects to soon manufacture fiberglass panels for the construction industry and is anticipating the development of other products for both the construction and automotive industries.

Fig 35: *"Thermoplastic Pellets"*

These products can be further recycled after they have reached their end-lives.

(ii) Packaging

Waste plastic bottles to sustainable filament yarn for apparel manufacture

The UK-based company PerPETual Global Technologies uses a proprietary technology to convert single-use waste plastic bottles into high-quality filament yarn for apparel manufacture. The company manufactures sustainable yarns (polyesters) for numerous applications, including knitting, weaving, and the production of mesh, fleeces, denim, automotive textiles, furnishings and technical textiles.

The company successfully developed and commercialized an environmentally sustainable and cost-effective process to reverse-engineer consumer waste PET bottles into high-quality, sustainable polyester. This process can directly replace the petrochemical-derived method used to produce conventional polyester.

PerPETual sells it yarns as sustainable polyester to more than 40 customers around the world, including major apparel brands like Adidas, Puma, H&M, Zara, C&A, and Decathlon.

The company, which manufactures its yarns in Nashik, Maharashtra state, India (approximately 100 miles north east of Mumbai), has recognized plastic bottles are, in fact, a valuable raw material resource.

INPUTS:

PerPETual converts over 2 million PET plastic bottles per day into filament yarns. Since the beginning of 2015, the company has recycled more than 2.1 billion plastic bottles.

The process uses 86% less water and consumes 75% less energy than conventional PET manufacturing. PerPETual's products save around 0.7 barrels of oil and 0.2m^3 of landfill waste for every 1 MT of PET waste recycled[57].

The company's goal is to recycle more than 50 million bottles a day by the end of 2021, which is still only a small fraction of the estimated 1.5 billion bottles discarded every day around the world.

TECHNOLOGY:

PerPETual's technology provides a new way to break down plastic bottles into sustainable esters. These can be used as the building blocks to manufacture all polyethylene terephthalate (PET) based products, such as polyester textiles, bottles, film and packaging. The technology truly allows PerPETual to be part of the circular economy.

PerPETual's technology is scalable and able to realize manufacturing cost efficiencies. At scale, PerPETual can already produce sustainable esters using plastic bottles as an input, costing lower than traditional petrochemical ester plants.

PerPETual's innovative process operates at a materially lower temperate as compared to conventional polyester manufacturing.

OUTPUTS:

The company manufactures approximately 20 MT of sustainable ester per day (c. 7,300 MT per year), 79% of which is sold for apparel and home textile use.

Polyester has several properties that make it appealing for these markets. It is a highly durable material (ideal for workwear), is the fabric of choice for sportswear, given its ability to "wick" away sweat and its elastic nature, and can be used to make bags (rucksacks and shoulder bags), denims and furnishings.

57. https://www.perpetual-global.com/about/

(iii) Chemicals

ENERKEM + PARTNERS: MSW TO BIO-METHANOL

In March 2019, a consortium of leading chemical companies, comprising Shell, Air Liquide, Nouryon (formerly AkzoNobel Speciality Chemicals) and Enerkem announced they had formed a joint venture in partnership with the Port of Rotterdam to create Europe's first advanced waste-to-chemicals facility. The Dutch Ministry of Economic Affairs and Climate Policy and the City of Rotterdam also support the project.

The commercial-scale project plans to leverage Enerkem's proprietary technology to convert MSW into bio-methanol at the Port of Rotterdam, where more than 2 million MT of MSW are imported annually. Non-recyclable waste materials like unrecoverable plastics and other mixed waste streams are likely to be used as feedstocks, thereby providing a sustainable alternative to landfilling and incineration.

The facility is expected to convert 360,000 MT of MSW into 220,000 MT (270m liters) of bio-methanol. This is a building block used in the manufacture of a broad range of everyday products, in addition to being used as a renewable vehicular biofuel. The waste represents the annual amount disposed by 700,000 households. CO_2 emission savings are estimated at 300,000 MT[58], compared with conventionally producing methanol from fossil fuels conventionally from natural gas or coal.

It is planned that Air Liquide will provide oxygen for the project, Nouryon will provide hydrogen, and Nouryon and Shell will purchase the facility's sustainable methanol output. A final investment decision on the project is expected to be made later in 2019.

Enerkem, a Canadian specialist technology company in the production of biofuels (ethanol and methanol) from waste, also operates a commercial-scale facility in Alberta, Canada.

VELOCYS + PARTNERS: BIOMASS AND MSW-TO-JET FUEL

UK company Velocys is working in collaboration with British Airways and Shell to develop a commercial-scale waste-to-renewable jet fuel plant at Immingham, near Hull on the Humber Estuary, UK. The project is part-grant funded by the UK's Department for Transport under the Future Fuels for Flight and Freight Competition.

The project plans to take hundreds of thousands of tonnes per year of post-recycled household and office waste destined for landfills or incineration and convert it to jet fuel, using Velocys's proprietary small-scale micro channel Fischer-Tropsch technology. Its technology converts waste materials, through a process of gasification and catalytic synthesis to biofuels.

58. https://enerkem.com/news-release/w2c-rotterdam-project-welcomes-shell-as-partner/

Velocys claims the jet fuel produced in this way is expected to deliver a 70% reduction in greenhouse gas emission and 90% reduction[59] in particulate matter emissions as compared to conventional petroleum-derived jet fuels.

TECHNOLOGY:

The Velocys technology takes the post-recycled waste and gasifies the feedstock into a syngas of carbon monoxide and hydrogen at around 700°C, without combustion, using a controlled amount of oxygen.

The Fischer-Tropsch process converts the syngas into paraffinic hydrocarbons.

These raw Fischer-Tropsch products are upgraded by hydro-cracking, isomerisation and fractionation to produce premium hydrocarbon jet fuel.

CURRENT STATUS:

The project is currently at an engineering-study stage and is fully funded by the partners. A final investment decision is expected in 2020. The identified site is subject to planning and permitting. A planning application is expected to be submitted in summer 2019.

Subject to planning permission and funding, once fully operational, the plant is expected to take hundreds of thousands of tonnes per year of post recycled waste— otherwise destined for landfills or incineration—and convert it into 60 million liters of clean-burning sustainable jet and road fuel each year.

This is expected to lead to a net CO_2 saving of over 80,000 MT year, equivalent to taking 30,000 cars off the road.

(iv) Other

COMMERCIAL COMPOSTING

Composting involves the aerobic decomposition of organic solid wastes. It is typically used to convert the organic fraction of the waste stream (e.g. food and agricultural waste residues) to a commercially useful soil conditioner or fertilizer favorable for plant growth.

59. https://www.velocys.com/wp/wp-content/uploads/Velocys_UK_waste-to-jet-fuel_brochure_181128.pdf

INPUT WASTES:

Input materials in composting operations typically comprise the segregated organic fraction of MSW from homes, offices, restaurants and canteens. This includes food wastes (e.g. meat, fish, shellfish, bones, bread, vegetables, fruit, coffee, tea, kitchen paper, dirty napkins), garden and agricultural waste (e.g. leaves, grass, flowers, twigs, wood, soil) and animal waste.

TECHNOLOGY/PROCESS:

Microorganisms eat the organic waste, breaking it down into its simplest components. The humus (finished compost) they produce is rich in fiber and inorganic nutrients like phosphorus, potassium and nitrogen, which makes a natural fertilizer beneficial to the environment.

Composting needs four components to work effectively:

- **Carbon** - for energy (microbial oxidation of carbon produces heat)
- **Nitrogen** - to grow and reproduce more organisms to oxidize the carbon
- **Oxygen** - for oxidizing the carbon (i.e. the decomposition process). Oxygen is accessed by turning over the compost every 1-2- days
- **Water** - a certain level of moisture is required to maintain activity

The correct ratios of these four components will cause the compost pile to heat up to ideal conditions and maintain an optimal decomposition rate. A temperature of 50˚C-70˚C is seen as optimal.

There are three phases of composting:

1) **Initial mesophilic phase:** decomposition carried out under moderate temperatures by mesophilic microorganisms
2) **Thermophilic phase:** As temperature rises (to around 65-70˚C), decomposition is carried out by thermophilic bacteria
3) **Maturation phase:** As high-energy compounds dwindle, temperature starts to decrease, mesophiles once again begin to dominate

Commercial composting can take the form of centralized large-scale operations, in several formats:

IN-VESSEL COMPOSTING

In-vessel composting confines composting materials to a container, such as a metal or plastic tank, where airflow and temperature can be closely controlled. Air circulation is typically metered in via buried tubes that allow fresh air to be injected under pressure and exhaust air to be extracted through a bio-filter. Temperature and moisture conditions are monitored using probes in the mass to allow the maintenance of optimum aerobic decomposition conditions.

In-vessel composting is generally used for municipal-scale organic waste processing, including the final treatment of sewage bio-solids, to a safe and stable state for reclamation as a soil amendment.

AERATED STATIC PILE COMPOSTING

Aerated static pile composting is the simplest and cheapest method of composting at scale, suitable for large volumes of livestock manure, yard debris and other feedstocks. A fan is used to push and pull air through the pipes during composting, providing circulation for controlled aeration. The air pipes are used to increase oxygen supply and help control temperature and odor.

Fig 36: *"Wheel loader working on a compost pile in a biogas plant"*

Fig 37: *"Aerated Static Pile Composting"*

WINDROW COMPOSTING

Suitable for producing large volumes of compost for agriculture, Windrow composting is commonly used to handle garden waste, shrubs trees, animal manure and crop residues. Requiring a compost turnover machine, the rows are intended to promote air circulation, remove moisture and improve porosity and oxygen content.

Fig 38: *"Windrow Composting"*

OUTPUTS:

Compost is rich in nutrients and used as a common soil conditioner and fertilizer in organic farming, landscaping, horticulture, urban agriculture and gardening. Compost mitigates soil erosion and can also be used as a final top cover for landfilling.

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