WORLD ENERGY COUNCIL

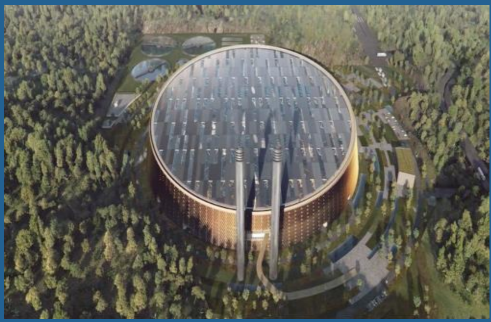
World Energy Resources

Waste to Energy | 2016

TABLE OF CONTENTS

Florida waste-to-energy plant cuts landfilled waste by 90%

World's biggest waste-to-energy plant to be built in China



Company to lead 13 MW landfill gas-to-energy projects in South Africa

Dubai issues tender for waste-to-energy plant

Industry flags concerns about upcoming EU emission limits for incinerators

Waste-to-Energy

World first Carbon Capture & Storage at Oslo waste-to-energy plant

Biomethane from organic waste could quadruple by 2021

Researchers develop microbial fuel cell with food waste derived catalysts

Company to develop Asian hazardous waste-to-energy plant

Oslo burns so much trash for energy they're importing rubbish

KEY FINDINGS

1. Treating residual waste with various Waste-to-Energy (WtE) technologies is a viable option for disposal of Municipal Solid Waste and energy generation. There are many factors that will influence the choice of technology and every region will have to properly assess its specific context to implement the most reasonable solution.

2. The global WtE market was valued at US$25.32 billion in 2013, a growth of 5.5% on the previous year. WtE technologies based on thermal energy conversion lead the market, and accounted for 88.2% of total market revenue in 2013.

3. The global market is expected to maintain its steady growth to 2023, when it is estimated it would be worth US$40 billion, growing at a CAGR of over 5.5% from 2016 to 2023.

4. Europe is the largest and most sophisticated market for WtE technologies, accounting for 47.6% of total market revenue in 2013. The Asia-Pacific market is dominated by Japan, which uses up to 60% of its solid waste for incineration. However, the fastest market growth has been witnessed in China, which has more than doubled its WtE capacity in the period 2011-2015.

5. Biological WtE technologies will experience faster growth at an average of 9.7% per annum, as new technologies (e.g. anaerobic digestion) become commercially viable and penetrate the market.

6. From a regional perspective, the Asia-Pacific region will register the fastest growth over this period (CAGR of 7.5%), driven by increasing waste generation and government initiatives in China and India; and higher technology penetration in Japan.

7. It is estimated that global waste generation will double by 2025 to over 6 million tonnes of waste per day and the rates are not expected to peak by the end of this century. While OECD countries will reach 'peak waste' by 2050, and East Asia and Pacific countries by 2075, waste will continue to grow in Sub-Saharan Africa. By 2100, global waste generation may hit 11 million tonnes per day.

8. The need to increase the share of renewable energy and reduce GHG emissions, along with raising environmental consciousness to protect the environment from polluting and unsustainable practices such as landfilling, will have a positive impact on WtE market development.

9. WtE remains a costly option for waste disposal and energy generation, in comparison with other established power generation sources and for waste management, landfilling.

10. Combustion plants are no longer a significant source of particulate emissions owing to the implementation of governmental regulations on emission control strategies, reducing the dioxin emissions by 99.9%.

11. At a global level, the influence of WtE on energy security may well be on a limited scale, especially in terms of power generation. While waste production is projected to increase, WtE suffers from limited levels of resource availability and hence power generation capacity, in comparison with the conventional energy resources.

INTRODUCTION

Waste is an inevitable product of society, and one of the greatest challenges for future generations is to understand how to manage large quantities of waste in a sustainable way. One approach has been to minimise the amount of waste produced, and to recycle larger fractions of waste materials. However, there still is a considerable part of undesired end-products that must be taken care of, and a more suitable solution than simple landfilling needs to be found.

The waste management sector faces a problem that it cannot solve on its own. The energy sector, however, is considered to be a perfect match, because of its need to continuously meet a growing energy demand. Waste is now not only an undesired product of society, but a valuable energy resource as well. Energy recovery from waste can solve two problems at once: treating non-recyclable and non-reusable amounts of waste; and generating a significant amount of energy which can be included in the energy production mix in order to satisfy the consumers' needs.

The interaction between waste management solutions and energy production technologies can vary significantly, depending on multiple factors. Different countries across the world choose to adopt different strategies, depending on social, economic and environmental criteria and constraints. These decisions can have an impact on energy security, energy equity and environmental sustainability when looking at the future of the energy sector. If waste-to-energy (WtE) technologies are developed and implemented, while following sustainability principles, then a correct waste treatment strategy and an environment-friendly energy production can be achieved at the same time, solving challenges in both the waste management and energy sectors.

DEFINITIONS AND CLASSIFICATIONS

Municipal Solid Waste (MSW) is classified and defined in various ways depending on the country and what waste management practices are employed. For example, Eurostat (2012) identifies MSW as produced by households or by other sources such as commerce, offices and public institutions. The waste is collected by or on behalf of local authorities and is disposed of through the waste management system[1]. The differences in MSW definitions create uncertainty when assessing waste management and national performance, but also inconsistency in data collection as there are overlaps between waste categories across countries, making disaggregation difficult[2].

When considering waste as an energy resource, it is important to take into account the composition of the different types of available waste. Municipal Solid Waste (MSW) from

[1] Eurostat (2012a) 'Generation and treatment of municipal waste (1 000 t) by NUTS 2 regions',
[2] European Environment Agency (2013)

residential, industrial and commercial sources is the most common waste stream used for energy recovery. However, construction waste, bio-waste from agriculture and forestry activities, hazardous waste and many others also can be considered feasible for energy recovery, depending on their specific composition, their energy content and the specific needs of society in terms of waste disposal. Table 1 shows the different recognised sources of waste and their respective compositions.

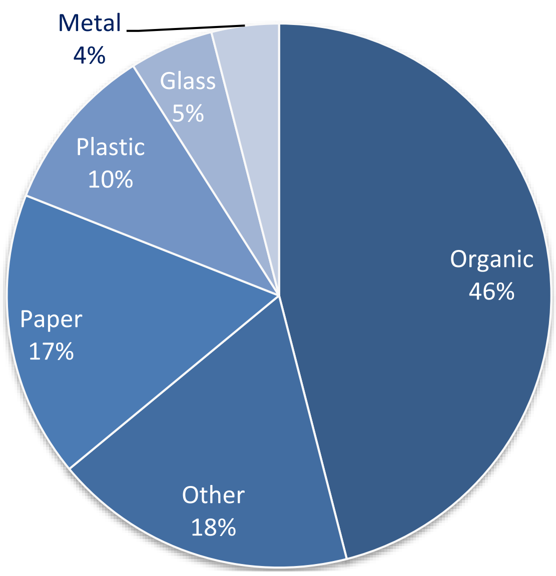
TABLE 1: TYPES AND SOURCES OF WASTE

<table>
<tr><th colspan="2">Source / type</th><th>Composition</th></tr>
<tr><td rowspan="5">Municipal solid waste (MSW)</td><td>Residential</td><td>Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (e.g. bulky items, consumer electronics, white goods, batteries, oil, tyres), household hazardous wastes, e-wastes.</td></tr>
<tr><td>Industrial</td><td>Housekeeping wastes, packaging, food wastes, wood, steel, concrete, bricks, ashes, hazardous wastes.</td></tr>
<tr><td>Commercial & institutional</td><td>Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes, e-wastes.</td></tr>
<tr><td>Construction & demolition</td><td>Wood, steel, concrete, soil, bricks, tiles, glass, plastics, insulation, hazardous waste.</td></tr>
<tr><td>Municipal services</td><td>Street sweepings, landscape & tree trimmings, sludge, wastes from recreational areas.</td></tr>
<tr><td colspan="2">Process waste</td><td>Scrap materials, off-specification products, slag, tailings, top soil, waste rock, process water & chemicals.</td></tr>
<tr><td colspan="2">Medical waste</td><td>Infectious wastes (bandages, gloves, cultures, swabs, blood & bodily fluids), hazardous wastes (sharps, instruments, chemicals), radioactive wastes, pharmaceutical wastes.</td></tr>
<tr><td colspan="2">Agricultural waste</td><td>Spoiled food wastes, rice husks, cotton stalks, coconut shells, pesticides, animal excreta, soiled water, silage effluent, plastic, scrap machinery, veterinary medicines.</td></tr>
</table>

Sources: Hoornweg & Bhada-Tata (2012); ETC/SCP (2013)

The major fractions of solid waste include paper, organic material, plastics, glass, metal and textiles. Figure 1 illustrates the composition of solid waste worldwide. As can be seen, nearly half of the produced waste from society is organic. Specific waste products deriving from construction, industrial and commercial waste are not specified in this figure, but in some cases can represent the majority of a region's waste production.

FIGURE 1: COMPOSITION OF GLOBAL MSW



Source: Hoornweg & Bhada-Tata (2012)

There are numerous technical criteria that have to be met for WtE adoption, and take precedence over other considerations to ensure the reliable operation of a would-be WtE facility. Some of the commonly considered factors are mentioned below.

Waste as a Fuel

The choice of WtE technology will be largely dependent on the nature and volume of the incoming waste stream. A key factor is the energy content (calorific value) of the waste, which determines how much energy can be extracted from it. Table 2 shows approximate net calorific values for common fractions of MSW.

TABLE 2: APPROXIMATE NET CALORIFIC VALUES FOR COMMON MSW FRACTIONS

Fraction	Net Calorific Value (MJ/kg)
Paper	16
Organic material	4
Plastics	35
Glass	0
Metals	0
Textiles	19
Other materials	11

Source: ISWA (2013)

For example, as a general rule, WtE incineration should only be considered if the incoming waste stream has an average net calorific value of at least 7 MJ/kg (i.e. combustion process is self-sustaining). In addition, for optimal operation of the plant, the supply of combustible MSW should at least amount to 100,000 tonnes / year (but could be lower for plants in isolated areas)[3]. Seasonal changes in waste quality, such as during holidays and festivals, and local traditions which may impact the nature of waste must also be taken into consideration.

These requirements represent a specific challenge for WtE implementation in developing and emerging countries; where waste has significant water content and the organic fraction of the waste is relatively high, and sophisticated waste collection and transportation structures are not in place. In these cases, biochemical methods of energy conversion should be the preferred option. Meanwhile in China, improvements to existing incineration technology have enabled it to unleash the potential of WtE in the country, as described in the following case study.

[3] ISWA (2013)

WTE INCINERATION FOR CHINA

Waste is a subject of growing concern in China, as is the case in many emerging economies. The country generates about 300 million tonnes of MSW annually, and this figure is expected to exceed half a billion tonnes per annum by 2025[4]. In addition, simple landfilling of waste is leading to secondary pollution – either through methane leakage or by the contamination of groundwater.

Since the turn of the century, China has made a concerted effort to utilise WtE as a part of its waste management strategy. However, even this is not straightforward. MSW has a high proportion of food waste, resulting in high moisture content and a relatively low net calorific value (3-5 MJ/kg on average, compared to 8-11 MJ/kg in Europe). The waste also has seasonal variations, giving it complicated heating properties.

Incineration technology originated in Europe is not well suited to treat waste with the mentioned properties. Therefore, research in China has developed new incineration plants based on circulating fluidised bed (CFB) technology to recover energy from its waste. CFB technology is proven to be better suited for high moisture content waste, hence making it potentially attractive for implementation in other emerging economies. Dioxin levels reported from these new plants are lower than EU standards. The plants are also capable of processing sewage sludge and other waste sludges, of which China produces 40 million tonnes a year, once the waste is pre-dried. Ongoing research is targeted towards reducing the amount of sewage-sludge ash produced from incineration, and integrating the pre-dried ash with MSW to produce more fuel for the plant.

There are currently 28 CFB WtE plants in operation in China, the largest of which was built in 2012 and processes 800 tonnes of waste per day[5].

Waste, as a fuel, cannot compete with fossil fuels due to its low calorific value and heterogeneous composition. The Table 3 below shows as an example calorific values of selected fuels.

[4] Coolsweep, 2014, Global analysis of the waste-to-energy field
[5] Zhejiang University, 2015

TABLE 3: CALORIFIC VALUES OF SELECTED FUELS

Fuel	Calorific Value (MJ/kg)
Natural gas	36-50
Diesel	46
Black coal, various types	29-32.7
Lignite briquettes	21
Refuse derived fuel, in Germany	13-23
Wood	15
Crude lignite	10
Residual waste, unsorted, in Austria	8-12
Residual waste, unsorted, in China	3.5-5

Source: Ecoprog (2015[6])

APPLICATIONS

Electricity

Electricity can be produced from waste through direct combustion, and the released heat is utilised to produce steam to drive a turbine. This indirect generation has an efficiency level of about 15% to 27%, with modern plants reaching the higher end of the range. The electrical efficiency rate from incineration is usually higher than from gasification due to lower operating temperatures, steam pressure and overall energy required to run the plant.

Gasification and pyrolysis processes produce a combustible synthetic gas (syngas) that can either be used to produce electricity through the process presented above, or further refined and upgraded to for direct generation in a gas turbine or engine. Greater efficiency

[6] Ecoprog (2015)

is realised from direct combustion in gas turbines or engines, rather than from a steam turbine[7].

Heat

The conventional method to generate heat from waste is though combustion or syngas expended in a boiler system to produce steam. Technological advancements made possible the upgrade of syngas to methane that can be injected in the gas network and utilised in domestic boilers. This procedure could be more effective as the heat is produced in a high efficiency boiler where is needed. However, a more efficient method of up to 90% is to burn waste in cement kilns where the heat is directly used in the process, though the market potential is small. Tackling challenges of finding long term customers for the heat produced and finances to support the infrastructure costs is essential to make this process commercially viable[8].

Combined Heat and Power (CHP)

WtE plants can produce heat and power simultaneously using a CHP unit that raises the overall efficiency to up to 40%. In this context, the heat that is generated during electricity production is captured and utilised. A constant demand for the heat will yield the highest economic benefits, and it depends on the location of the plant and the possibility to transfer the heat to, for instance, industrial sites that utilise heat in their operations or district-heating systems that can send it to the neighbouring community or commercial properties.

The challenge of operating CHP systems in the optimal way is to know the relative value of electricity and heat in order to prioritise what should be produced more according to demand. This happens because there is a trade-off between heat and electricity, meaning that as more heat is produced, the output of electricity will decrease due to less amount of energy available. Conversely, gas engines are not affected in the same way[9].

Transport Fuels

WtE processes can also generate fuels that can be utilised in the operation of transport vehicles. The syngas produced by gasification and pyrolysis technologies can be consumed in vehicle engines if upgraded to bio-methane. Syngas can also be used to make synthetic diesel and jet fuel. Other fuels include hydrogen, ethanol and biodiesel. Oil can be produced through pyrolysis that requires further treatment to be converted to petrol or diesel. Transport fuels can be a more efficient method of utilising energy from waste if the energy requirement for making the fuels is low. However, this is not always the case

[7] Defra (2014)
[8] Defra ibid
[9] Defra ibid

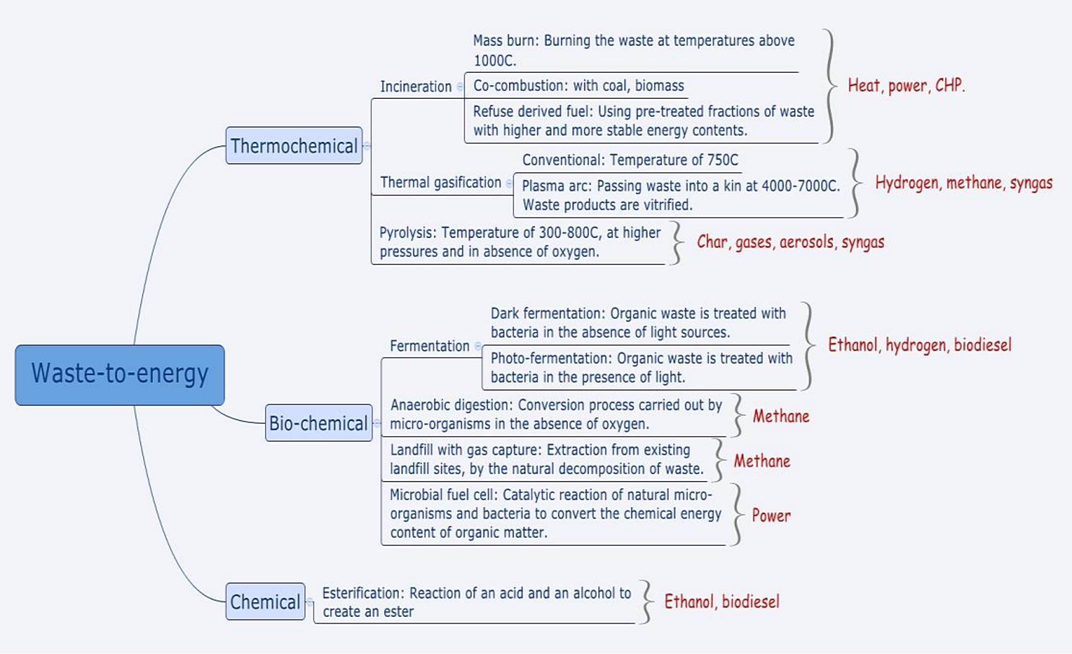
and an example of an energy intensive process is the purification of syngas necessary for making it effective to run an engine.

1. TECHNOLOGIES

Energy conversion from waste can be obtained by utilising different technologies. Each one of these WtE solutions has specific characteristics, and can be more or less feasible depending on many parameters. Factors include the type and composition of waste, its energy content, the desired final energy form, the thermodynamic and chemical conditions in which a WtE plant can operate, and the overall energy efficiency.

The following list of WtE technologies[10] gives an overall picture of the available options on the market. There are also new developments and research projects aimed at promoting alternatives to the most mature and established technologies.

FIGURE 2: CURRENT TECHNOLOGIES



THERMOCHEMICAL CONVERSION

Thermo-chemical conversion technologies are used to recover energy from MSW by using or involving high temperatures. They include combustion or incineration, gasification and pyrolysis. The main difference among these technologies is the amount of excess air and

[10] Lo Re, Piamonti, & Tarhini (2013)

temperature within the process that leads to the conversion of final product CO_2 and water, or to intermediate useful products keeping aside other technological differences. The dry matter from MSW is most suitable feedstock for thermochemical conversion technologies.

Combustion

Combustion of MSW is the complete oxidation of the combustible materials contained in the solid waste fuel, and the process is highly exothermic. During combustion of solid waste, several complex processes happen simultaneously. Initially, the heat in the combustion chamber evaporates the moisture contained in the solid waste and volatilises the solid waste components. The resulting gases are then ignited in the presence of combustion air to begin the actual combustion process. The process leads to the conversion of waste fuel into flue gas, ash and heat. The heat released is used to produce a high-pressure superheated steam from water, which is sent either to the steam turbine that is coupled with generator to produce electricity, or used to provide process steam. It is important to note that the bottom and fly ashes that are formed by the inorganic constitutes of the waste affects the energy balance through its mean heat capacity, even though it is not particularly participated in the combustion process[11]. Depending on the bottom ash treatment options, ferrous and non-ferrous metals can also be recovered and the remaining ash can be further enhanced to be used for road construction and buildings[12].

Gasification

Solid waste gasification is the partial oxidation of waste fuel in the presence of an oxidant of lower amount than that required for the stoichiometric combustion[13]. The gasification process breaks down the solid waste or any carbon based waste feedstock into useful by-products that contain a significant amount of partially oxidised compounds, primarily a mixture of carbon monoxide, hydrogen and carbon dioxide. Furthermore, the heat required for the gasification process is provided either by partial combustion to gasify the rest or heat energy is provided by using an external heat supply[14]. The produced gas, which is called syngas, can be used for various applications after syngas cleaning process, which is the greatest challenge to commercialise this plant in large scale. Once the syngas gas is cleaned, it can be used to generate high quality fuels, chemicals or synthetic natural gas (SNG); it can be used in a more efficient gas turbines and/or internal combustion engines or it can be burned in a conventional burner that is connected to a boiler and steam turbine[15]. However, the heterogeneous nature of the solid waste fuel makes the gasification process very difficult together with the challenges of syngas cleaning, and there are not many large-scale stand-alone waste gasification plants in Europe.

[11] Consonni, & Viganò (2012)
[12] Grosso, et al. (2011)
[13] Arena (2012), Higman, (2011), Eremed et.al. (2015)
[14] Arena (2012), Higman (2011)
[15] Arena (2012)

Pyrolysis

Pyrolysis of solid waste fuel is defined as a thermo-chemical decomposition of waste fuel at elevated temperatures, approximately between 500°C and 800°C, in the absence of air and it converts MSW into gas (syngas), liquid (tar) and solid products (char). The main goal of pyrolysis is to increase thermal decomposition of solid waste to gases and condensed phases. The amount of useful products from pyrolysis process (CO, H_2, CH_4 and other hydrocarbons) and their proportion depends entirely on the pyrolysis temperature and the rate of heating[16].

It is important to note that the mechanical treatment ahead of gasification, sensitivity to feedstock properties, low heating value of waste fuel, costly flue gas clean-up systems, difficulty of syngas clean-up and poor performance at small scale have been a great challenge during gasification of MSW[17].

Table 4 describes the main differences between the waste thermal processes described above.

TABLE 4: COMPARISON BETWEEN PYROLYSIS, GASIFICATION AND COMBUSTION

Pyrolysis	Gasification	Combustion
Normally no air	Sub stoichiometric air Exothermic/Endothermic	Excess air Very exothermic
Only heat (external or internal)	Lower total volumetric flow	Higher volumetric flowrate
Want liquid, gases not desired	Lower fly ash carry over	Fly ash carry over
Pollutants in reduced form (H2S, COS)	Pollutants in reduced form (H2S, COS)	Pollutants in oxidised form (Sox, Nox etc)
Higher char	Char at low temperatures Vitrified slag at high	Bottom ash

[16] Higman. (2011)
[17] Consonni, & Viganò (2012)

Scale: ~10 tonnes/day	Scale: ~100 tonnes/day	Scale: ~1500 t/day
No additional oxygen (only heat)	Some additional oxygen (or air)	Much additional oxygen (or air)

Source: Asme (2013[18])

BIOCHEMICAL CONVERSION

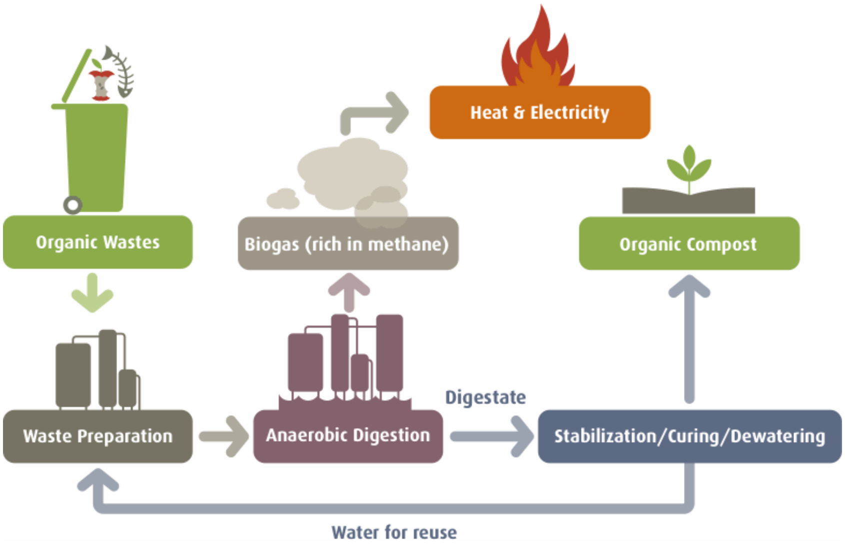
Biological conversion technologies utilise microbial processes to transform waste and are restricted to biodegradable waste such as food and yard waste. Accordingly, the wet matter from the MSW (the biogenic fraction) and agricultural waste are the most suitable feedstocks for biochemical conversion technologies.

Anaerobic Digestion (AD)

AD is a process by which organic material is broken down by micro-organisms in the absence of oxygen, producing biogas, a methane-rich gas used as a fuel, and digestate, a source of nutrients used as fertiliser. The time of operation per cycle, meaning how long it takes for the organic waste to be processed by an AD plant, is usually 15 to 30 days. The biogas naturally created in sealed tanks is utilised to generate renewable energy in the form of electricity or heat with a combined heat and power unit (CHP). The bio-fertiliser is pasteurized to make it pathogen free and can be applied twice a year on farmland, successfully replacing the fertilisers derived from fossil fuels. The technology is widely used to treat wastewater and can also be effectively employed to treat organic wastes from domestic and commercial food waste, to manures and biofuel crops[19].

[18] Goff, Norton and Castaldi (2013)
[19] http://www.biogas-info.co.uk/about/

FIGURE 3: ILLUSTRATION OF AD PROCESS TREATING BIODEGRADABLE MSW



Source: Iona Capital (2016)

The anaerobic digestion process occurs in multiple steps and involves a community of micro-organisms, as follows:

- Hydrolysis – complex polymers are broken down by hydrolytic enzymes into simple sugars, amino acids and fatty acids
- Acidogenesis – simple monomers are broken down into volatile fatty acids
- Acetogenesis – the products of acidogenesis are broken down into acetic acid
- Methanogenesis – methane and carbon dioxide are produced

There are many types of AD systems that operate in different ways as well. They are usually classified as follows:

- **Mesophilic or Thermophilic**: The former system operates at temperatures between 25-45°C, while the latter process requires higher temperatures of 50-60°C. Thermophilic systems have a faster biogas production per unit of feedstock and m^3 digester, and are more effective at clearing the digestate of pathogens. As they need more energy for heating, these systems have higher costs and require more management than mesophilic ones.
- **Wet or Dry**: this refers to the AD feedstock, but the difference between the two is not significant. Wet AD is 5-15% dry matter and can be pumped and stirred; while dry AD is over 15% dry matter and can be stacked. Dry AD tends to be cheaper to operate as there is less water to heat and there is more gas production per unit of feedstock. In contrast, wet systems require lower capital costs for installation, but dry systems tend to be favoured for MSW treatment.
- **Continuous Flow or Batch Flow**: most AD plants operate with a continuous flow of feedstock because the costs are lower and tend to give more biogas per unit of

input. It is technically challenging to open the digester and restart the system from cold every few weeks. However, there are dry systems that operate on batch flow, and multiple batch digestors with staggered changeover time can be used to overcome peaks and troughs in gas production.

- **Single or Multiple Digestors**: AD occurs in different stages, and wet systems may require multiple digestors to ensure efficiency of the process. Multiple digestors have higher capital and operating costs, require more management, but can offer more biogas per unit of feedstock.
- **Vertical Tank or Horizontal Plug Flow**: Vertical tanks take feedstock in a pipe on one side and digestate overflows through a pipe on the other. Horizontal plug flow is chosen when there is more solid feedstock. The former is cheaper and simple to operate, but presents the risk of having the feedstock for inappropriate periods of time resulting in possible economic losses. The latter is expensive to build and operate, but the rate of feedstock flow in the digester can be highly controlled[20].

The choice of AD technology will depend on many factors such as type of feedstock, co/single digestion, space (e.g. plants will have to have a small footprint in urban areas), desired output (e.g. more biogas for energy production, waste mitigation, bedding, digestate), infrastructure and available grants/financing. It is very flexible as it can be designed in multiple ways, according to the context in which is intended to operate.

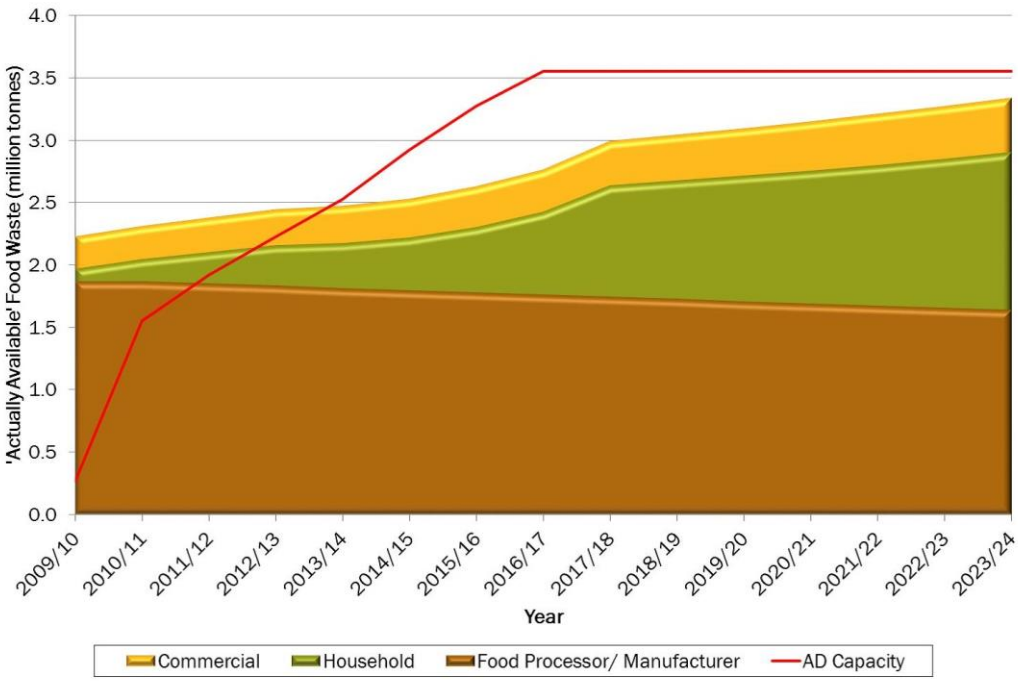
The feedstock usually requires pre-treatment, depending on the kind available. For instance, waste food from supermarket will require removal of all packaging and screening for contaminants such as plastics and grit; while others such as manure or waste crops will need to be homogenised to reach the consistency desired for optimum fuel output[21].

AD is a promising technology with multiple benefits for a wide range of stakeholders ranging from the local community, farmers to government. It is considered to be the optimum method for handling food waste in an environmentally safe way. While it is not a new technology, since it dates from as back as 1800s, and experienced continuous growth and technical development throughout the recent years, the market is rather small with huge room for expansion. In the UK for instance, the biggest drawback for development is the lack of feedstock access. This is not given by a lack of organic waste in general, but by the inability to readily access the streams of waste, a large proportion of it remaining in the residual waste streams. It has been observed that the AD capacity exceeds the 'actually available' food waste, even though it is estimated that UK produces 15 million tonnes of food waste per year. As of 2014, there were 2.8 million tonnes of AD capacity in the United Kingdom designed to treat organic waste from food processing and manufacturing, household and commercial enterprises. The capacity is forecasted to increase to 3.5 million

[20] http://www.biogas-info.co.uk/about/ad/
[21] WRAP (2016)

tonnes in 2016/2017 and stall until 2023/2024. Figure 4 below shows that there is already an excess of AD capacity on the market, and not enough feedstock available to readily support the new facilities. Appropriate regulation to incentivise more effective separation of waste at source and preventing the disposal of organic waste in landfills is necessary to increase feedstock, which will enable better use of existing AD capacity[22].

FIGURE 4: CAPACITY GAP BETWEEN 'ACTUALLY AVAILABLE' FOOD WASTE AND AD CAPACITY IN UK



Source: Eunomia Research & Consulting (2014[23])

Fermentation

Fermentation is a process by which organic waste is converted into an acid or alcohol (e.g. ethanol, lactic acid, hydrogen) in the absence of oxygen, leaving a nutrient-rich residue. Fermentation for the production of bio-ethanol, which is of great importance in the transport sector as it is a clean fuel, is done by pure cultures of selected yeast strains. Yeast fermentations are carried out both as continuous and batch fermentations, although often the batch process is preferred due to less probability of contamination. Practical bio-ethanol fermentation plants are large, and an optimal sized plant produces about 200,000-300,000 tonnes of ethanol per year.

[22] Eunomia (2014)
[23] Eunomia Ibid

Bio-ethanol production in Europe and USA is mainly from starchy substrates such as corn, wheat and triticale, whereas in Brazil the substrate is mainly sourced from sugarcane. There is a focus on developing the effective utilisation of lignocellulosic biomass as substrate because it allows a major increase of renewable substrate availability, without diminishing the availability of food plants. However, this is still significantly more expensive since pre-treatment of cellulosic substrates is required through enzymatic, thermal and acid treatments. Research attempts to increase enzyme activity and reduce enzyme costs to allow economically viable, large-scale enzyme applications. Recent processes to disintegrate biomass developed to raise ethanol yield and decrease the energy demand include alkaline, acid and solvent treatments. The by-product of ethanol fermentation is residual silage after distillation and is usually used for animal feeding, with recent focus on finding ways to recover the energy contained in it[24].

TABLE 5: COMPARISON BETWEEN AD AND FERMENTATION

Anaerobic Digestion	Fermentation
Hydrolysis is the initial step	Hydrolysis is the initial step
Final process step is methanogenesis	Final process step is distillation
Primary output product is biogas	Primary output products are alcohols
Currently utilised worldwide to treat MSW as well as other feedstocks	Currently, few facilities exist worldwide for MSW; facilities using other feedstocks do.

Landfill with Gas Capture

Landfills are a significant source of greenhouse gas emissions, and methane in particular can be captured and utilised as an energy source. Organic materials that decompose in landfills produce a gas comprised of roughly 50% methane and 50% carbon dioxide, called landfill gas (LFG). Methane is a potent greenhouse gas with a global warming potential that is 25 times greater than CO_2. Capturing methane emissions from landfills is not only beneficial for the environment as it helps mitigate climate change, but also for the energy sector and the community.

[24] Braun, R. et al (2010) Recent development in Bio-energy Recovery through fermentation

Applications for LFG include direct use in boilers, thermal uses in kilns (cement, pottery, bricks), sludge dryers, infrared heaters, blacksmithing forges, leachate evaporation and electricity generation to name a few. LFG is increasingly being used for heating of processes that create fuels such as biodiesel or ethanol, or directly applied as feedstock for alternative fuels such as compressed natural gas, liquefied natural gas or methanol. The projects that use cogeneration (CHP) to generate electricity and capture the thermal energy are more efficient and more attractive in this sense.

The process of capturing LFG involves partially covering the landfill and inserting collection systems with either vertical or horizontal trenches. Both systems of gas collection are effective, and the choice of design will depend on the site-specific conditions and the timing of installation. They can also be employed in combination and an example is the utilisation of a vertical well and a horizontal collector. As gas travels through the collection system, the condensate (water) formed needs to be accumulated and treated. The gas will be pulled from the collection wells into the collection header and sent to downstream treatment with the aid of a blower. Depending on the gas flow rate and distance to downstream processes, the blowers will vary in number, size or type. The excess gas will be flared in open or enclosed conditions to control LFG emissions during start up or downtime of the energy recovery system, or to control the excess gas, when the capacity for energy conversion is surpassed[25].

The LFG treatment of moisture, particulates and other impurities is necessary, but the type and the extent will depend of the sort of energy recovery used and the site-specific characteristics. Minimal treatment can be employed for boilers and most internal combustion systems, while other internal combustion systems, gas turbines and micro-turbine applications will require more sophisticated procedures with absorption beds, biological scrubbers and others, to remove substances such as siloxane and hydrogen sulphide.

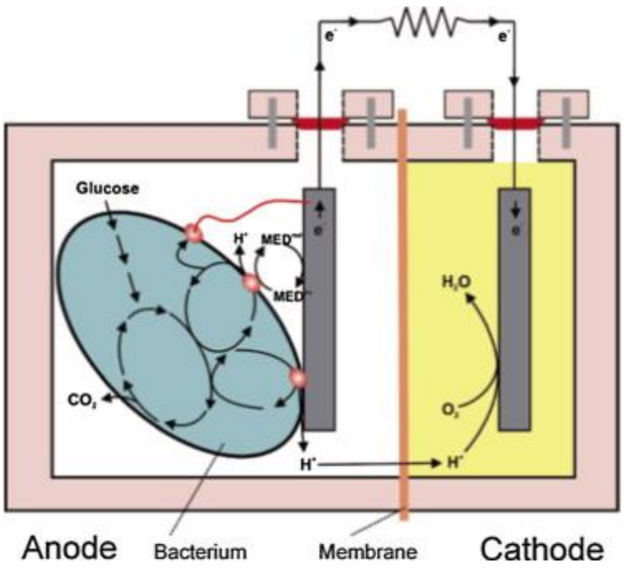
One million tonnes of MSW in the USA produces around 12,233m^3 per day of LFG and will continue to produce it for another 20 to 30 years after the MSW has been landfilled. LFG is considered a good source of renewable energy, and has a heating value of about 500 British thermal units (Btu) per standard cubic foot[26]. Benefits of using this WtE process go beyond abatement of GHG emissions and offset the use of non-renewable resources, to include other economic advantages such as revenue for landfills, energy costs reduction for LFG energy users, sustainable management of landfills, local air quality improvement and job creation.

[25] EPA (2014)
[26] EPA ibid

Microbial Fuel Cell (MFC)

MFCs are biochemical-catalysed systems in which electricity is produced by oxidising biodegradable organic matters in the presence of either bacteria or enzyme[27]. Bacteria are more likely to be used in MFCs for electricity production, which also accomplish the biodegradation of organic matters and wastes. Good sources of microorganisms include marine sediment, soil, wastewater, fresh water sediment and activated sludge. MFCs consist of anodic and cathodic chambers separated by a proton exchange membrane. The anodic part is usually maintained in the absence of oxygen, while the cathodic can be exposed to air or submerged in aerobic solutions. Electrons flow from the anode to the cathode through an external circuit that usually contains a resistor, a battery to be charged or some other electrical device. Figure 5 below shows a typical two-chamber MFC[28].

FIGURE 5: ILLUSTRATION OF A TYPICAL TWO-CHAMBER MICROBIAL FUEL CELL



Source: Rahimnejada, M. *et al.* (2015)

The activity in a MFC consists of microbes that oxidise substrates in the anodic chamber, releasing CO_2 and producing electrons and protons in the process. The electrons are absorbed by the anode and transported to the cathode through an external connection. After crossing the proton exchange membrane, the protons enter the cathodic chamber

[27] Rahimnejad et al. (2011)
[28] Reddy et al. (2010)

where they combine with oxygen to form water. In this reaction, the substrate is broken down to CO_2 and water, with the derivative of electricity production.

This technology is suitable for small scale electricity generation in remote areas or in places where the use conventional batteries is expensive or dangerous. An example is the use of MFCs to power sensor devices that monitor corrosion and pressure levels in deep-sea oil and gas pipelines. Their applications extend to bio-hydrogen production, waste water treatment (e.g. odour removal, desalination, and sulphides removal), biosensors (as sensor for pollutant analysis and process monitoring) and bioremediation.

This technology is considered to be still in its infancy and faces practical challenges such as low power and density. Limitations relate to the inefficiency of the cell to generate power to a sensor or a transmitter continuously. Solutions in this area include expanding the surface area of the electrodes or to use capacitors to store energy released by the MFC and used in short bursts when needed. Research in this field proposed a design of MFC that amplifies power generation by removing the proton exchange membrane, which creates internal cell resistance, as follows: single chamber, stacked and up flow MFC. Furthermore, MFCs cannot operate at low temperatures because microbial reactions are slow at low temperatures. Commercial application of this environmentally friendly WtE technology is not yet feasible due to a lack of manufacturing capacity to produce the reactor cathodes and high costs of electrode materials[29].

CHEMICAL CONVERSION

Esterification

The esterification process involves the reaction of a triglyceride (fat/oil) with alcohol in the presence of an alkaline catalyst such as sodium hydroxide. A triglyceride has a glycerine molecule as its base with three long fatty acids attached. The alcohol reacts with the fatty acids to form a mono-alkyl ester, or biodiesel, and crude glycerol, used in the cosmetic, pharmaceutical, food and painting industries. The alcohol used is usually either methanol, which produces methyl esters, or ethanol, with ethyl esters. The base applied for methyl ester is potassium or sodium hydroxide, but for ethyl ester the former base is more suitable. The esterification reaction is affected by the chemical structure of the alcohol, the acid and the acid catalyst. Biodiesel is used in the transportation sector and can be produced from oils and fats through three methods: base catalysed transesterification of oil; direct acid catalysed transesterification of oil and; conversion of the oil to its fatty acids and then to biodiesel. Base catalysed transesterification is the most economical process to produce biodiesel[30].

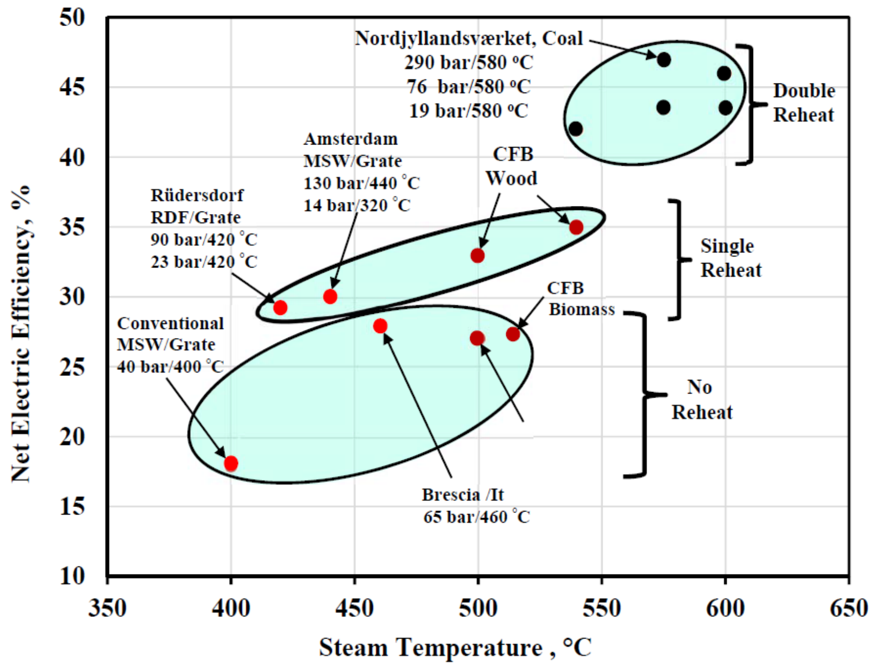
[29] Logan et al. (2015)
[30] http://www.see.murdoch.edu.au/resources/info/Tech/waste/

EFFICIENCIES AND PHYSICAL CONSTRAINTS

The energy performance of WtE plants can be affected by a variety of factors. The unfavorable physical properties of the solid fuel entail a larger combustion chamber with long residence times for complete combustion. Besides, the unfavorable composition of the waste fuel implies low boiler efficiency due to high moisture content, significant auxiliary consumption due to high ash content, costly and sophisticated flue gas treatment system to effectively remove unwanted pollutants, presence of highly corrosive species in the combustion products, thus the maximum pressure and temperature adopted in the steam cycle are much below than those adopted in fossil fuel-fired plants[31].

In addition, these facilities are of smaller scale and are forced to use relatively inefficient cycle configurations that reduce the productivity of the steam turbine. On average, the capital investment of WtE plants is approximately three times higher than the present coal-fired power plants[32].

FIGURE 6: NET ELECTRIC EFFICIENCY OF WTE PLANTS COMPARED TO MODERN BIOMASS AND COAL FIRED POWER PLANTS



RDF – Refuse Derived Fuel CFB – Circulating Fluidised Bed It - Italy

[31] Consonni, Viganò & Eremed (2014)
[32] Themelis and Reshadi (2009)

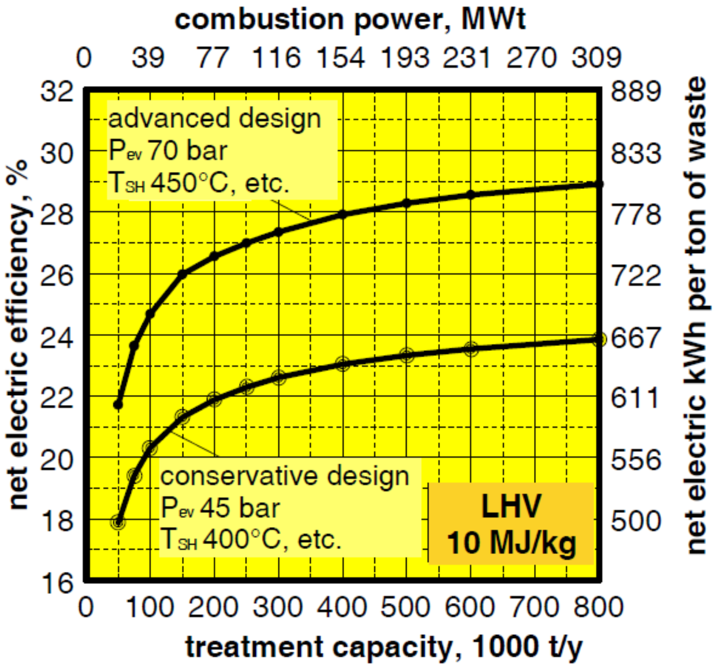
Source: Hunsinger (2011) & Vainikka et.al (2013)

Compared to coal fired power plants, the energy performance of WtE plants is quite low as shown in Figure 6. This is because coal and waste fuel have different properties and characteristics such as quality of the fuel, size of the fuel particles, fuel composition, ash and moisture content and variable nature of the waste. Therefore, this affects the design of the combustion chamber, the amount of air and time required for complete combustion, stack losses and environmental concerns. Even though it is possible to find a double reheat coal fired plant with very high steam parameters up to 300 bar and 650°C, most WtE plants operate with steam parameters of around 40 bar/ 400°C due to corrosion problems.

The crucial parameters that increase the efficiency of WtE plants including the limitation of each factor are briefly described below. The efficiency of a plant can be boosted by finding ways to further increase the steam temperature and pressure while avoiding the corrosion problem of boiler tubes. Research in this area focuses on redesigning the boiler and adopting different steam cycle configurations, which includes external superheating by combining natural gas turbine or gas engines to a modern WtE plant[33] and steam reheating. The WtE plant of Amsterdam is the first highly efficient waste fired plant with a net electric efficiency of around 30% with steam reheating concept and low steam condensation pressure, which aids plant efficiency[34]. However, this process is affected by the water availability and ambient air conditions, depending of the type of condenser used. The efficiency of WtE plants can be further increased by up to 34% with an advanced combustion control system to reduce the excess air, a reduction of the boiler exit temperature to minimise stack losses and utilisation of CHP systems[35].

[33] Consonni, Viganò & Eremed (2014)
34 Murer (2011)
35 Consonni, Viganò & Eremed (2014)

FIGURE 7: EFFECT OF STEAM PARAMETERS AND SCALE



Source: Consonni, Viganò and Bogale (2014[36])

EMERGING TECHNOLOGIES

Hydrothermal Carbonisation (HTC)

Hydrothermal Carbonisation is the chemical acceleration of natural geothermal processes using an acid catalyst. It is considered a highly efficient process which replicates the natural process of coal generation using a combination of heat and pressure to chemically transform bio-waste into a carbon dense material with similar or better properties as fossil fuel. The wet waste is heated in a 'pressure cooker' between 4 and 24 hours at relatively low temperatures of around 200°C. The feedstock is transformed into a coal-like product called 'hydrochar' (coalification) and is potentially ideal for carbon sequestration[37].

The feedstock needs pre-processing prior to carbonisation and any glass and metals should be removed. The input needs to have high moisture (>70%) in comparison with other typical thermal treatment feedstocks. The process requires and acid catalyst such as citric acid. While any organic material can be 'coalified' including lignocellulosic materials, it is best to use food waste owing to suitable moisture content[38].

36 Ibid Consonni et al. (2014)
[37] Stanley (2013)
[38] Stanley (2013)

This system emits the lowest amount of GHG of any biomass to fuel conversion process and the only by-product is toxin-free water. HTC is a highly efficient and environmentally sustainable method of converting biomass in solid fuel. Table 6 below shows a comparison to other biofuel production processes in terms of carbon efficiency.

TABLE 6: CARBON EFFICIENCY OF SEVERAL BIOFUEL PRODUCTION PROCESSES

Carbon Efficiency	Process
90%	Hydrothermal Carbonisation
70%	Alcoholic fermentation
50%	Anaerobic digestion / biogas
30%	Other biomass conversion processes (e.g. pyrolysis, gasification)
10%	Composting

Source: www.antanco.co.uk (2016)

Other advantages of this technology include scalability, fast and continuous operation, odour free and silent operation, hygenisation of products, available market for the 'hyrochar', attractive investment for private investors, thus reducing public debt[39].

Dendro Liquid Energy (DLE)

DLE is a recent German innovation in biological treatment of waste, and presents high potential in the WtE field, being a close to 'zero-waste' technology. The reactor of DLE plants is able to process mixed waste from plastics to wood logs, producing clean fuels for electricity generation such as carbon monoxide and hydrogen. In comparison with anaerobic digestion, this technology is up to four times more efficient in terms of electric power generation, with additional benefits of no emissions discharge, effluence or nuisance problems at plant sites. The process leaves 4% to 8% inert residue that can be used as aggregate or sent to landfill.

This process system presents the following specific advantages:

[39] Hernandez (2015)

- Small decentralised low-cost units
- There is no combustion involved, so no emissions abatement technology involved
- Works at moderate temperatures of 150 - 250°C, depending on the type of input material
- Accepts a wide variety of material, both wet and dry
- Energy conversion at 80% and high energy efficiency
- CO_2 neutral
- The resulted syngas is free of particulates and tar[40]

[40] Ghougassian (2012)

2. ECONOMICS & MARKETS

HISTORIC AND CURRENT TRENDS

The global WtE market was valued at US$25.32 billion in 2013, a growth of 5.5% on the previous year. WtE technologies based on thermal energy conversion lead the market, and accounted for 88.2% of total market revenue in 2013[41].

Europe is the largest and most sophisticated market for WtE technologies, accounting for 47.6% of total market revenue in 2013. Increasing industrial waste, coupled with stringent EU-wide waste legislation have been the major drivers for the European market. Switzerland, Germany, Sweden, Austria and Netherlands lead installation capacity within Europe. The Asia-Pacific market is dominated by Japan, which uses up to 60% of its solid waste for incineration. However, the fastest market growth has been witnessed in China, which has more than doubled its WtE capacity in the period 2011-2015[42].

On the other hand, market growth in the developing economies of Sub-Saharan Africa has been largely inhibited by the large up-front costs for WtE, as well as a general lack of awareness of the benefits of WtE implementation. Low-cost landfilling remains the preferred option for the processing of waste in these parts of the world.

DRIVERS AND KEY DYNAMICS

The development of WtE market happened in contexts that created opportunities through several different drivers. These drivers include growing use of renewable energy resources, increasing amounts of waste generation globally, waste management regulations, taxes and subsidies, climate change policies to curb GHG emissions, technological advancements, access to talent, new financing opportunities, new global trends such as low fossil fuel prices, environmental degradation, circular economy, green business models, industrial symbiosis (companies that work in partnerships to share resources); and improved public perception of WtE[43].

Trends in Waste Generation

As modern society moves towards an increasing level of urbanisation, and with a growing population that demands higher consumption of goods and greater energy needs, the topic

[41,3] Global News Wire (2015)
[42] Yuanyuan (2015)
[43] Coolsweep

of waste management and energy recovery from waste becomes central for future scenarios of sustainable development.

When it comes to waste generation as a product of society (with a particular focus on MSW), the specific characteristics of each region, country, and even city or conurbation of the world must be taken into account. These characteristics include:

- Population growth
- Rate of urbanisation
- Gross domestic product (GDP) and other economic development parameters
- Public habits, i.e. different consumption rates of different goods
- Local climate

A recent study conducted by the World Bank[44] shows the levels of waste generation per capita, for different regions of the world. As can be seen in Table 7, regions where the standards of living are higher and there is a greater consumption of goods (such as OECD countries) produce greater amounts of waste in kg/capita-day, while underdeveloped countries such as those in the South Asian Region (SAR) present lower waste generation levels per capita. Furthermore, within each single region, there can be large variations of waste production depending on local conditions and specific dynamics.

TABLE 7: WASTE GENERATION DATA IN 2012, BY REGION

Region	Total Urban Population (millions)	Total Urban MSW Generation (tonnes/day)	Urban MSW generation per capita (kg/day)
Africa	261	169 120	0.65
East Asia & Pacific	777	738 959	0.95
Eastern & Central Asia	227	254 389	1.12
Latin America & Caribbean	400	437 545	1.09

[44] Hoornweg&Bhada-Tata (2012)

Middle East & North Africa	162	173 545	1.07
OECD	729	1 566 286	2.15
South Asia	426	192 411	0.45
Total	**2 982**	**3 532 255**	**1.19**

Source: Hoornweg&Bhada-Tata (2012)

Figure 8 explicitly proves that economic development has a significant impact on the levels of waste generated in a certain territory. It shows a strong correlation between waste generation per capita and gross national income per capita (based on purchasing power parity).

FIGURE 8: WASTE GENERATION PER CAPITA (KG/DAY) TO GROSS NATIONAL INCOME (GNI) RATIO IN 2014 IN SELECTED COUNTRIES

Source: Navigant Research, World Bank (2014)

As a result of these waste generation rates, and taking into account projections for population growth and the increase in urbanisation, the World Bank estimates that global waste generation will nearly double by 2025 to over 6 million tonnes of waste per day. Table 8 justifies this prediction by showing the increase in waste generation per capita for each region. As can be noted from these results, OECD countries as of today produce approximately half of the world's urban waste. However, it is estimated that by 2025 the influence of these countries on global waste generation will be strongly reduced. This is because of the efforts in terms of waste reduction and waste management in OECD countries, and a significant increase in waste generation per capita and overall waste production for countries in developing regions of the world (e.g. in the East Asian and Pacific region). In addition, global waste generation rates are not expected to peak by the end of this century. While OECD countries will reach 'peak waste' by 2050, and East Asia and Pacific countries by 2075, waste will continue to grow in Sub-Saharan Africa. By 2100, global waste generation may hit 11 million tonnes per day[45].

TABLE 8: PROJECTED WASTE GENERATION DATA FOR 2025, BY REGION

Region	Total Urban Population (millions)	Total Urban MSW Generation (tonnes/day)	Urban MSW generation per capita (kg/day)
Africa	518	441 840	0.85
East Asia & Pacific	1 230	1 865 380	1.52
Eastern & Central Asia	240	354 811	1.48
Latin America & Caribbean	466	728 392	1.56
Middle East & North Africa	257	369 320	1.43
OECD	842	1 742 417	2.07
South Asia	734	567 545	0.77
Total	**4 287**	**6 069 705**	**1.42**

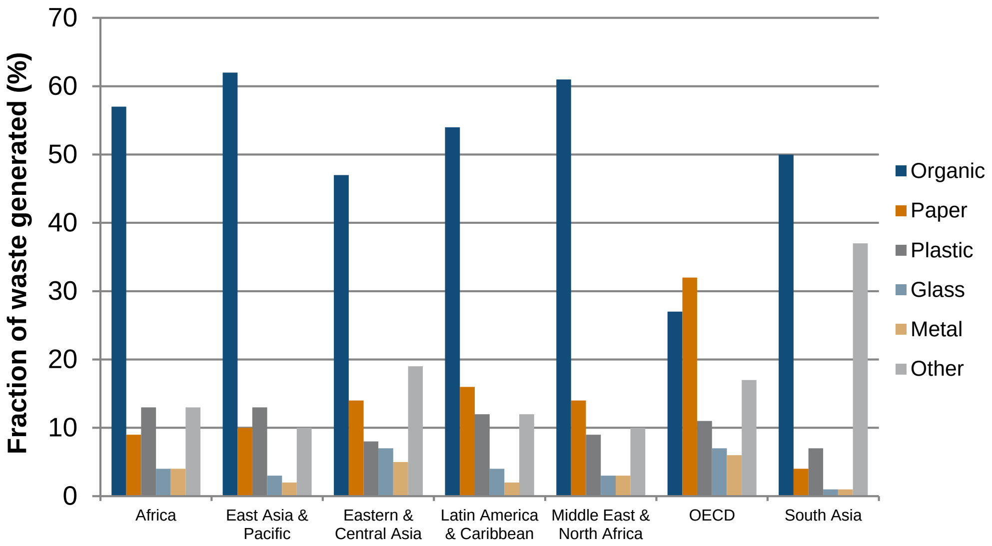
Source: Hoornweg & Bhada-Tata (2012)

Waste composition varies greatly between different areas, regions and countries of the world. It is influenced by many different factors such as culture, economic development,

[45]Hoornweg, Bhada-Tata & Kennedy (2013)

climate, and energy resources. Based on previous considerations, Figure 9 illustrates the different waste composition on a regional level. As can be seen, countries in the OECD region strongly reflect the profile of the high income society, while poorer countries such as in East Asia and in the Pacific present large fractions of organic waste products.

FIGURE 9: COMPOSITION OF SOLID WASTE IN 2012, BY REGION



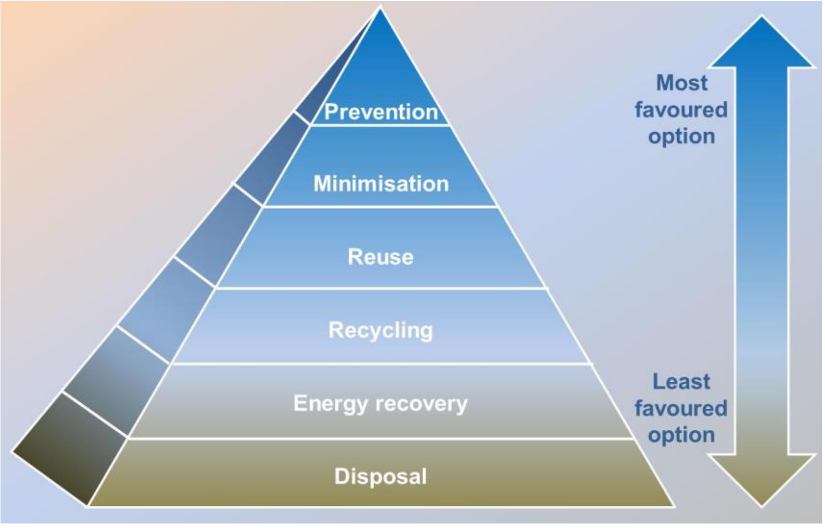
Source: Hoornweg&Bhada-Tata (2012)

Having considered differences across waste sectors for different regions of the world, similar observations can be made by focusing on the energy sector: increased economic and industrial development requires higher energy needs, most often in the form of electricity; different climates require different energy needs in the form of heating or cooling; growth in population and developing transport sectors will bring variations in the demand for fuels. Therefore, WtE technologies must be able to combine the specific needs of the waste sector with the demands of society in the energy sector in order to operate in the most efficient manner.

Overlap between Energy and Waste Management Sectors

Considering all these factors, which will surely contribute to an overall increase of waste generation, it is very important to manage these quantities of undesired materials. The waste management hierarchy, as shown in Figure 10, describes the preferred course of action for managing waste. Different versions of the hierarchy are adopted, but they all follow a step-wise process for waste where prevention, minimisation, and reuse (& recycling) of waste products are prioritised.

FIGURE 10: THE WASTE MANAGEMENT HIERARCHY

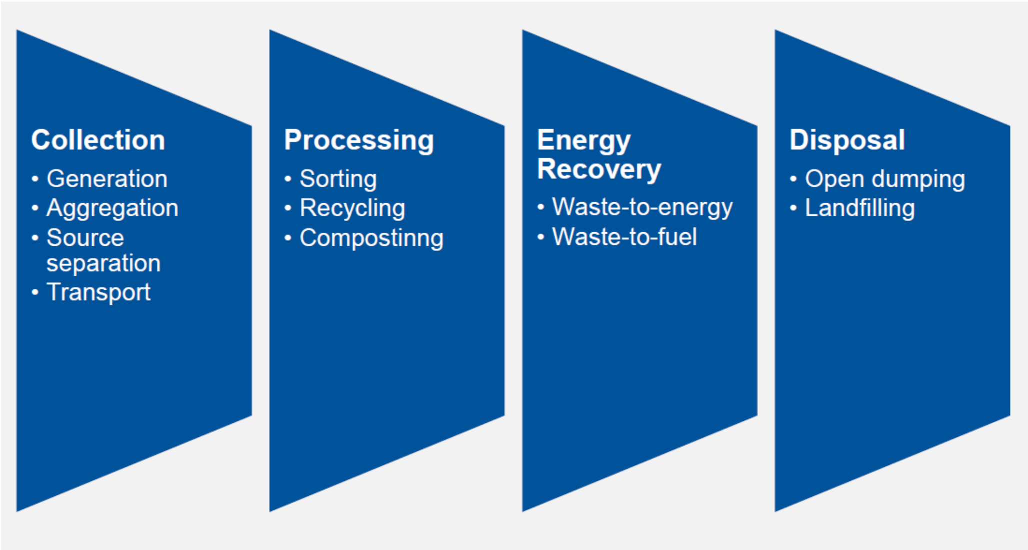


Source: Hughes (2013)

However, even by taking into account all these feasible solutions, there will always be a significant fraction of waste material that must be dealt with in a different way. WtE is a more convenient process than simple landfilling of waste, because of the beneficial side effect of producing useful energy in different forms. In this field, the waste sector is strictly connected to the energy sector. Waste materials, which originally have been used as specific products for societal needs, can be used for a second purpose: as a useful energy resource.

Sustainable waste management systems can then be developed based on the hierarchy, from waste collection to final disposal. However, in some contexts the waste hierarchy is not necessarily the most sustainable route for waste management, but adopting alternative process steps that use life cycle thinking which do not follow the hierarchy, can be a more sustainable solution. Figure 11 is an example of a waste management value chain that follows the waste management hierarchy.

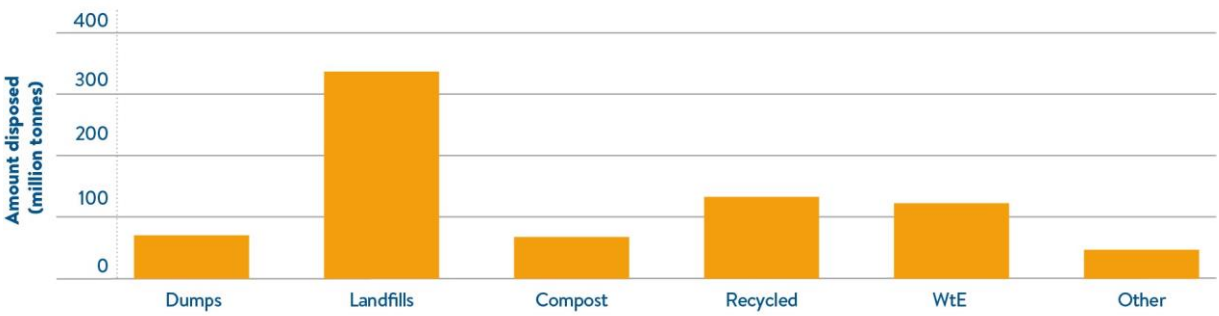
FIGURE 11: MANAGEMENT VALUE CHAIN FOR MSW



Source: Navigant Research (2014)

However, there remains a long way until a global sustainable waste management strategy is achieved. As of 2012, it is clear in Figure 12 that landfilling is by far the most utilised solution for waste disposal worldwide, despite being the least desirable waste management practice.

FIGURE 12: AMOUNT OF WASTE DISPOSED IN 2012, BY TECHNIQUE



Source: Hoornweg & Bhada-Tata (2012)

Depending on the income level and the development of each country, solutions like recycling and WtE are more or less developed. Of the estimated 122 million tonnes of waste that are used for WtE incineration – the most developed and established technology for energy recovery from waste – over 99% is treated in high-income level countries.

There is another aspect of the interaction between the waste management sector and the energy sector that is crucial for WtE plant operations. Because of the necessity to constantly deal with waste generation, WtE plants are typically required to operate at all times. In this way, the produced waste is always being managed and treated without any need for significant waste storage facilities, and thus the use of waste landfilling is minimised.

The potential of WtE implementation strongly depends on the specific economic, social and political conditions of the country where the implementation strategy must be carried out. The following classification for different countries is just one possible approach in order to analyse the various possible outcomes in terms of energy recovery from waste across the world.

TABLE 9: WTE STRATEGY IN HIGH INCOME COUNTRIES

High Income Countries		
Energy Sector	**Waste Sector**	**WtE Strategy**
Most competitive technologies implemented on both demand and supply side. Energy transmission and distribution infrastructure provides high quality services.	Practices based on sustainable waste hierarchy are implemented, with varying degrees of success. However, the undesired quantities of non-reducible and non-reusable materials remain significant.	Waste incineration with energy recovery (particularly CHP) is the preferred option. The technology is mature and well established on the market. Improvements in efficiency, generation flexibility and pollution control.
Greatest concerns related to environmental issues – improvements in efficiency of energy technologies, development in renewable energy technologies.	Hence, second-use energy recovery activities remain a feasible solution, despite environmental concerns linked on WtE technologies.	Other energy recovery solutions (gasification, pyrolysis, AD, bio-fermentation) can be locally implemented if system conditions yield a feasible economic outcome of each WtE project. Changing regulations can significantly impact technology deployment (e.g. rules on bio-residue sludge disposal).

TABLE 10: WTE STRATEGY IN MIDDLE INCOME COUNTRIES

Middle Income Countries		
Energy Sector	**Waste Sector**	**WtE Strategy**
There is a more diverse range of desirable energy vectors than in high income countries.	Inevitable increase of waste products (MSW, commercial waste, packaging); driven by industry, wealth and consumption.	Important to structure the WtE sector in relation to the needs and opportunities specific to that country.
Electricity is needed in areas where urbanisation is high, modern processes are developed, and a power grid is present.	Collection rates are variable, and there remains a sizeable informal waste sector.	Investments for implementation of WtE plants must be balanced by investments in the waste (and water) management sector.
Other required energy forms are domestic heating/cooling, process stream for industry, and synfuels for transportation (as seen in Brazil).	Collection, treatment and disposal of waste not highly supported by local and/or government authorities.	Regulatory framework around environment / emissions may not be present or effective. There needs to be an appropriate framework to drive WtE investments in a sustainable direction.

TABLE 11: WTE STRATEGY IN LOW INCOME COUNTRIES

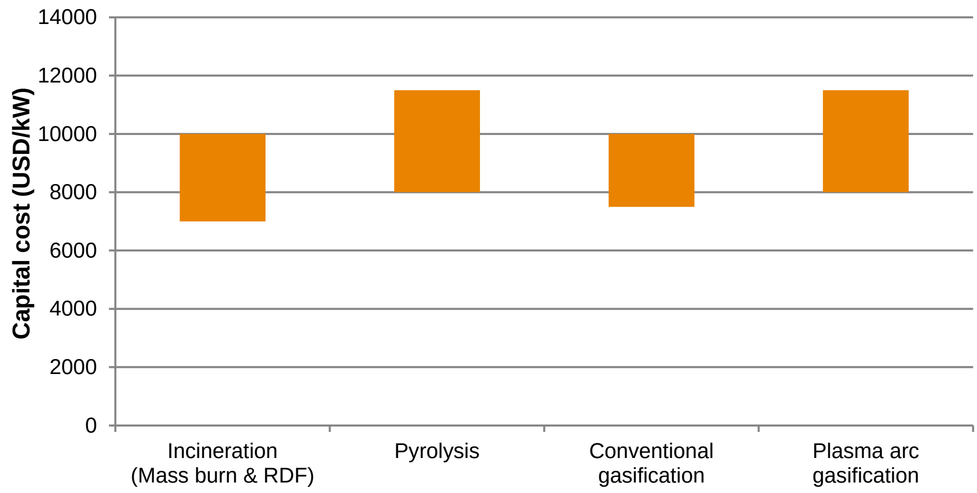
Low Income Countries		
Energy Sector	**Waste Sector**	**WtE Strategy**
Difficulty in implementing capital intensive T&D	Limited investments by governments and municipalities result in	Severe limitations in the energy and waste sectors negate the

infrastructure for electricity and gas.	inefficient or non-existent disposal of waste – not collected nor transported to treatment facilities / controlled landfill.	potential for WtE implementation.
At local level, difficulty in providing stand-alone, non-technological energy sources prevent people utilising energy as an everyday commodity.	Waste management is predominantly informal (waste picking). Recycling rates are high, but unregulated.	Local small scale WtE projects could provide improvements in terms of energy supply, waste management, pollution levels, job creation.

INVESTMENT COSTS

The capital investments for the construction and implementation of these technologies, and the costs needed to operate them for the entire lifetime of a chosen project can influence decisions when it comes to deciding the best WtE option. As of today, incineration of MSW still presents the most desirable economic conditions on the market, and is therefore the preferred option in most markets. Among the other thermal energy conversion technologies in the United States, capital costs for WtE incineration are slightly lower for the same plant output, as shown in Figure 13.

FIGURE 13: CAPITAL COSTS FOR THERMAL WTE POWER GENERATION TECHNOLOGIES IN THE UNITED STATES (15 MW OUTPUT)



Source: Stringfellow (2014)

Table 12 illustrates the differences in investment costs and main cost characteristics for WtE incineration across the world, depending on the economic conditions of different countries.

TABLE 12: INVESTMENT COSTS FOR WTE (INCINERATION)

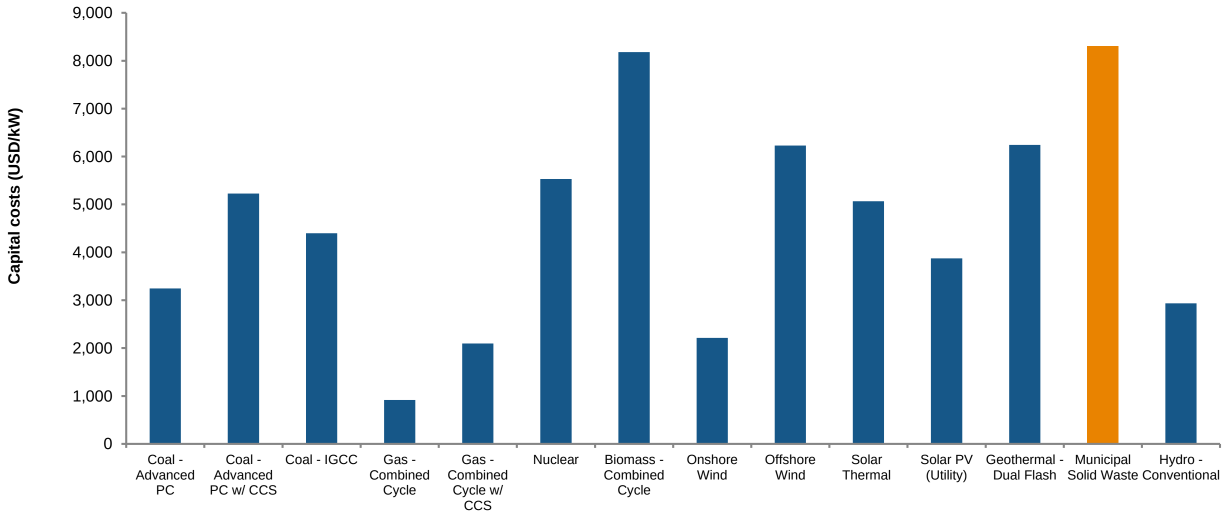
	Investment costs (US$/yearly tonnage capacity)	Characteristics
Low-income countries	300 – 500	Low labour costs Low calorific value of waste Low need for structural protection of equipment
Middle-income countries	400 – 600	Some requirements for structural protection of plant Slightly higher calorific value of waste Higher labour cost

High-income countries (EU and North America)	600 – 900	Stringent demands on equipment and safety High architectural standard of buildings

Source: ISWA (2013)

However, energy generation from waste remains a costly option, in comparison with other established power generation sources. Average capital costs for power generation from MSW remain much higher than for other sources in the United States, as seen in Figure 14, hence providing a barrier for the uptake of WtE across the country, particularly with the cheap availability of (shale) gas – MSW power generation capital costs are more than 8 times that of combined cycle gas plants.

FIGURE 14: CAPITAL COST ESTIMATES FOR UTILITY SCALE POWER GENERATION PLANTS IN THE UNITED STATES



Source: EIA (2013)

When it comes to the economics of various WtE technologies, the capital investment is generally high, but the costs differ according to the technology used and its size. Gasification technologies are usually more expensive than the usual grate combustion technologies. A gasification plant in the USA with a capacity of 750 tonnes per year would need roughly an investment cost of US$550 per annual capacity tonne. Investment costs for the same technology and similar plant size can also vary significantly, due to location, site implementations and land availability. For example, a comparison between two grate combustion WtE facilities located in different cities in China showed a significant difference in capital investment. Accordingly, the WtE plant in the city of Foshan, with a capacity of

462,000 tonnes per year had an investment cost of US$120 per annual capacity tonne, while the plant in Shanghai, with the capacity of 495,000 tonnes per year, had an investment cost of US$282 per annual capacity tonne. WtE technologies tend to have a lower investment cost in developing countries such as China even if they use Western technologies with CFB[46].

It is very difficult to generalise investment costs for each technology because there are regional differences in government incentives and market dynamics, and the amount of revenue gained depends on very localised conditions such as electricity prices, access to district heating network and recovery markets for recyclables (i.e. metals, paper, glass, plastic). In addition, investment costs of individual projects will vary depending on a range of factors including financing type, project developer, conditions in financial markets, maturity of technology, and risk and political factors[47].

ENERGY SECURITY

Issues linked to energy security differ from one country or region to the other, depending on the level of economic development and the availability and reliability of energy infrastructure. In regions such as Western Europe, growing concerns are linked to energy transmission and storage capacity limits, in relation to an increasing share of intermittent renewable energy generation units on the energy network. Considering the large fluctuations on the supply side, modern and efficient energy systems must be able to balance out these dynamic variations and transmit all the required energy to the demand side. If this is not achieved, then the population will be threatened by shortages of energy services. Also, due to the change of conditions within the energy sector (e.g. deregulation and privatisation of energy markets), the power flows in the existing network configuration do not necessarily follow original design criteria any more.

In less developed parts of the world, energy access remains a major challenge. As of 2013, 1.2 billion people still do not have access to electricity for lighting. Twice this population still relies on outdated stoves or open fires for cooking. It is estimated that more than 95% of people who cannot utilise modern energy services live in Least Developed Countries (LDCs) in sub-Saharan Africa and Asia[48]. Energy systems at present are not sufficiently developed to ensure reliable supplies of energy to the populace. Many inhabitants dwell in remote villages and small towns, and are often not connected to an electricity grid or to possible district heating and/or cooling networks. 84% of all people who do not have access to modern energy services live in rural areas[49]. Investment in a mature energy transmission system to cover the large distances between the energy generation centres and the end users has proven to be too costly for developing, but not yet thriving, economies. A realistic

[46] Themelis & Mussche (2013)
[47] Department of Energy & Climate Change (2012)
[48] IEA (2015) World Energy Outlook
[49] IEA

alternative to expanding the energy transmission and distribution infrastructure is the implementation, through both public and private sector investments, of mini-grids, stand-alone energy systems and other decentralised energy solutions which can be managed and operated locally.

At a global level, the influence of WtE on energy security may well be on a limited scale, especially in terms of power generation. While waste production is projected to increase, WtE suffers from limited levels of resource availability and hence power generation capacity, in comparison with the conventional energy resources. For example, with decreasing populations and increasing recycling rates, Sweden, Norway, Germany and the Netherlands currently do not generate enough waste to meet the demand of its WtE plants, and hence resort to import waste from neighbouring countries to keep the plants running. Developing countries with increasing energy needs will most likely rely on other types of energy for most of their generation capacity, limiting WtE to a minimal impact in this sense.

Furthermore, even in a theoretical case where waste could be seen as one of the main available energy resources of a country, the plants that will convert this resource into power are mostly characterised as base load units. This means that while available electricity capacity will increase, WtE plants will not be able to provide the necessary output flexibility required for grid balancing in regions such as Europe where the uptake of intermittent renewable power generation is a growing threat to energy security.

However, WtE could be seen as an interesting solution for energy security at a local level; a good example would be within the urban district heating and/or cooling market. Considering present and future trends both in population growth and in waste generation levels, and analysing the trends in waste recycling activities, the amount of available heat from waste treatment could be estimated and appropriately promoted.

WtE technologies would also gain traction as a reliable energy resource in remote, rural areas, and less developed countries where the energy system is not sufficiently developed. The investments necessary to build and correctly operate a WtE facility are significantly lower than those required to implement major energy transmission infrastructure to connect these areas to a main grid. Also, the fuel and primary energy source for these types of technologies is often already present on the local territory, thus fuel shipping costs can be avoided. This is the case in remote areas which are close to a reliable source of bio-waste. Forestry, agriculture and other processes which produce bio-waste can be the source of energy for local communities situated in proximity of these activities.

Depending on the needs of local communities in rural and decentralised areas, the required energy form can vary. Electricity may not always be as useful in regions of the world where electrical appliances are not commonly used. Production of biofuels, which is a privileged solution in specific developing countries, is often not important in these areas where motorised transportation is often limited. An interesting example could be the use of anaerobic digestion facilities, which are able to treat waste streams with high organic fractions and produce biogas with relatively high energy content, the biogas then being used locally for cooking and/or heating. These types of WtE can be implemented as large scale plants, which present high capital costs but can treat large quantities of waste, or as small scale plants, which might be a more feasible option for small communities in rural areas.

3. SOCIO-ECONOMICS

ROLE OF GOVERNMENTS

Depending on the nature of a country's society and on its level of development, policy targets can and do differ greatly within and outside the economic and environmental spheres of concern. WtE implementation can be promoted or otherwise because of local policies and regulations, different public perception of the challenges related to these technologies or even possible phenomena of political entanglement, which often arise in the waste management environment.

Also, the waste treatment policies which are selected by the local governments of a specific region, country or city (e.g. separated waste collection, recycling centres, waste import/export, etc.) can strongly change the feasibility of WtE technology projects. One of the reasons for the diversity of policy approaches to waste-to-energy across all levels is the acceptance of waste as a renewable fuel. Generally, MSW is considered as a renewable source, because it cannot be depleted. The Intergovernmental Panel on Climate Change has also recognised the potential of WtE in greenhouse gas mitigation. WtE projects are eligible for offset under the Clean Development Mechanism (CDM) protocol, by displacing fossil-fuel electricity generation and limiting uncontrolled methane release from landfill. However, such as in the United States, Germany, France and Italy, MSW is not considered 100% renewable, since portions of MSW consist of non-renewable elements. Hence, only the biogenic proportion of waste (food, paper, wood, etc.) is considered renewable and this is reflected in the policies on energy extraction from waste.

Regulations and Targets

The following policy measures are granted to encourage the development of WtE:

- Government subsidies for WtE, for example, renewables certificates, feed-in tariffs and renewable heat incentives
- Zero-waste policies: WtE has gained traction in major markets thanks to policies dis-incentivising landfill, hence ensuring more waste is treated further up the waste hierarchy. EU legislation has placed a ban on the disposal of all recyclable waste by 2025. As of 2015, 18 countries in the EU implement bans on landfill in some form[50]. Many countries also impose taxes on landfill, to make it less attractive for waste producers. In Sweden, where land for landfill disposal is relatively available and

[50] CEWEP, 2015

affordable (in the north of the country), WtE has nonetheless been a success (47% of all waste is converted to energy) as landfill fees are kept artificially high via taxation.

- Carbon taxes
- Renewables targets for WtE: These are usually made in conjunction with biomass. Table 13 shows policy targets related to waste-to-energy in countries where they exist.

TABLE 13: BIOMASS AND WASTE POLICY TARGETS IN SELECTED COUNTRIES

Country	Biomass and waste targets
China	30 GW by 2020
Germany	14% of heating by 2020
Indonesia	810 MW by 2025
Norway	14 TWh annual production by 2020
Philippines	267 MW by 2030
United States	Contained in state-level Renewable Portfolio Standards

Source: Navigant Research (2014)

Incentives

An incentive for WtE adoption that potentially cancels out the high capital investment costs comes from the several revenue streams that exist for WtE plant operators (other than the sale of energy). A direct comparison can also be made between WtE and landfilling activities in the waste management sector, regarding their operation. Capital costs and Operation & Maintenance costs are significantly higher in the case of WtE, but so are the revenues related to energy production. Also, additional costs related to environmental concerns may influence decision making.

Energy Production

If comparing any WtE technology with a traditional power plant which uses fossil fuels as an energy resource, the main benefit is given by the opposite pricing dynamics of the fuels. Waste is not a natural resource that can be utilised at a chosen rate, but it is a product of human activity that is constantly generated and therefore must be always managed in a convenient way. Currently, because of its status of unwanted product of society, waste is not considered a positive resource but more like a problem.

When looking at the dynamics of the energy market, with particular attention to the power market, this translates into the necessity to prioritise energy generation from WtE plants. Therefore, in normal conditions, WtE plants have priority dispatch on the market, thus ensuring constant revenue from energy generation throughout the entire lifetime of the plant.

Tipping Fees

Because waste is an undesired product of society, all waste producers, from municipalities to private sectors, must spend part of their economic resources for its collection, management and disposal. Typically, if waste is used for energy recovery, each waste producer is obliged to pay a tipping fee (or gate fee) to the WtE facility in order to dispose of the waste.

If looking at this topic from the energy sector point of view, it is clear how the presence of tipping fees creates a strong benefit for a WtE production plant. The fuel utilised for energy production does not lead to additional costs for the energy producer, as is the case for fossil fuel based energy generators, but instead generates additional revenues. Tipping fees are usually measured in revenue per received tonne of waste, and vary greatly depending on the country or region in which they are implemented. Revenue from tipping fees is usually the largest stream of income for a WtE facility. Tipping fees represent up to 70% of income for WtE plants in the United Kingdom[51].

If WtE tipping fees are too high, waste producers will seek alternative ways of disposing waste (e.g. illegal dumping). Also, overcapacity of WtE plants could lead to tipping fees being too low; however, tipping fees for WtE plants are usually based on a contract, and provide a guarantee for plant owners. Tipping fees may have to be subsidised for waste producers by central government / local authorities.

A comparison can be made between WtE and landfilling activities in the waste management sector. Tipping fee values for WtE and local landfilling can shift the final choice between these two options. Table 14 exemplifies the difference between WtE and landfill tipping fees in key markets.

[51] Hicks & Rawlinson (2010)

TABLE 14: WTE VS LANDFILL TIPPING FEES IN SELECTED COUNTRIES (DECEMBER 2013 CURRENCY EXCHANGE RATES)

	Average WtE tipping fees (US$/tonne)	Average landfill tipping fees (US$/tonne)
United Kingdom	148	153
Sweden	84	193
United States	68	44

Source: SWANA (2011); WRAP (2013)

There is a correlation between high tipping fees for landfill and the uptake of WtE, and vice-versa. In the United States, where fees for landfill are relatively low, only 12% of all solid waste was converted to energy in 2011, while 54% went to landfill[52]. Shifting economic factors will also have an effect on landfill disposal fees. For example, the current low oil and gas prices make transportation of waste to landfill cheap, hence making landfilling waste a more attractive option for waste producers. On the other hand, the decrease in available landfill facilities (from 6,326 in 1990 to 1,908 in 2013[53]) will push up the cost of sending waste to landfill.

Materials Recovery

Another possible income stream for (incineration) WtE operators is from the sale of materials recovered from the ash remaining after incineration. These include metals and glass, which have no heating value, but can be sold on the secondary (scrap) market. Recovered porcelain and tiles can be sifted to extract gravel, which is used in road construction. Materials recovery and other mechanical and biological treatment (MBT) processes can be integrated into the operations of WtE plants, producing extra value from the waste as well as a higher-grade fuel (SRF) for the plant. However, the current low commodity prices may make materials recovery unviable for WtE operators.

SOCIO-ECONOMIC IMPACTS

The overlap between the waste management and energy sectors touches several points linked to human society. The environmental implications of choosing specific WtE technologies can lead to social concerns and doubts on this type of solution. The need of waste treatment facilities close to urbanised areas is often in contrast with the public

[52] Williams (2011) Waste-to-energy success factors in Sweden and the United States
[53] United States Environmental Protection Agency (2015)

opinion to keep (incineration) WtE plants far away from cities because of health related issues.

There are also concerns that adoption of WtE treatment encourage production of waste, discourage recycling and are not compatible with the policies that promote a ‘zero-waste’ economy. In contrast, the countries that recover energy from waste also have high recycling rates, so there is no real basis for this claim. Moreover, there is no substantial evidence behind the fear that more WtE facilities translate into more wasteful management of resources. Developed countries focus on reducing waste generation, but this problem will exacerbate in developing countries due to population growth, urbanisation and higher rates of consumption. WtE plants that operate in areas where the waste hierarchy is applied are more likely to have stronger set of ‘zero waste’ policies, where residual waste is treated according to the energy value and environmental impact. For all of these reasons, and for many more, it is important to consider the social and political orientation of a specific location in terms of waste management before implementing and operating Waste-to-Energy facilities.

SOCIO-ECONOMIC BENEFITS

Focusing on MSW, the concentrated production of waste in urban areas is directly linked to a high energy demand in the same location. Therefore, a WtE facility which can treat waste – thus removing the complications related to land use for landfilling – and at the same time provide energy (electricity and heat) for the local population is a highly efficient solution. Incineration plants with appropriate emission control systems are largely used in countries (i.e. in northern Europe) where land availability is scarce and population density is high.

On the other hand, other types of waste can be produced far away from where the energy demand is high. This is typically the case of bio-waste from forestry activities or agriculture. In this case, the distances from the waste production site and the urban centres can be significant. For these situations, it is important to find a WtE technology that can recover energy from the waste and transfer it to the final users without having to build large infrastructure to connect these two parts of the system. An interesting choice could be an anaerobic digestion process in order to produce biogas and/or biofuels, which can then be more easily transported to where they are needed or sold on the market.

WtE facilities bring additional benefits in terms of employment and educational opportunities. Typical employment for a waste incineration plant of 50,000 tonnes per annum capacity would be 2 to 6 workers per shift. For a 24-hour operation, a typical plant would work on a three shifts system. For example, the WtE industry in the United States employed around 5,350 people nationwide in 2014, working at 85 specific sites. There were also additional 8,600 jobs created outside the sector. The jobs generated by the sector are usually well paid, stable and support the local economy[54].

Also, the plant staff will most likely receive vocational training. New WtE plants are more likely to engage with the communities as this is not only beneficial in the light of receiving project acceptance and support, but also with regards to community integration. Accordingly, they are often built with a visitors centre to enable local groups to see the facility and learn about how it operates[55].

WASTE-TO-ENERGY POTENTIAL IN ETHIOPIA

The 50 MW WtE incineration plant under construction in Addis Ababa is touted not only as a much-needed solution to the city's growing waste problem, but also as the first of many to be developed in the country. The US$120 million project is expected to come online in early 2017, and will process 350,000 tonnes of waste a year. The power station will be Ethiopia's first baseload plant, providing 24-hour electricity for at least 330 days of the year, and will also be the first WtE facility in Sub-Saharan Africa[56]. The Ethiopian Government has identified WtE as an important part of its strategy to reduce the country's emissions, and feasibility studies on WtE adoption have been undertaken in other cities, with developers looking to expand adoption to locations in Dire Dawa, Adama, and Mekelle.

However, the development of the project, and successful operation, face a number of challenges. Analysis shows the low calorific value of the incoming waste stream will lower the power output of the plant by as much as 44%. There is also a lack of local technical expertise required to operate the plant. While the plant is partly funded by the World Bank, low energy prices and the absence of supplementary income streams and incentives (e.g. tipping fees and carbon credits) mean the plant will struggle to recoup its costs over its operational lifetime.

The waste management system in Addis Ababa is also underdeveloped. Food and paper waste are rarely separated at source. The vast majority of MSW generated in Addis Ababa is collected informally. There are private companies that collect waste in the city for a fee of about ETB 10 (US$ 0.47) per month, but very few citizens can afford this. These issues contribute to making WtE incineration not particularly viable in the city.

The hope is that the plant's operation would lead to the development of a viable waste management system in Addis Ababa. The Ethiopian Electric Power Corporation (EEPCo), who will run the plant, is collaborating with the city's

[54] Michaels (2014)
[55] Defra (2013)
[56] http://www.eepco.gov.et/project.php?pid=27&pcatid=9

administration to ensure that waste collection for the plant is streamlined. While the plant will employ 100 skilled personnel, it is estimated that thousands of jobs will be created with the newly created waste collection system. It would be of interest to monitor the development of the project and the plant's operation, especially in the first 5 years, to evaluate the project's success.

SAFETY

WtE technologies, in particular incineration, produce pollution and carry potential health safety risks. There is extensive literature comprising numerous studies that investigated several aspects of the linkage between the discharged pollutants from waste incinerators and health conditions such as cancer. Waste incinerators have been highly scrutinised by the public health agencies, NGO activists and the general public, which influenced the legislators to impose stricter limits on emissions. Older MSW incinerators posed higher health risks and some epidemiological studies found a positive correlation between groups of congenital anomalies of the population living in the vicinity of a waste combustion plant. However, many studies have inconclusive results or their assessment methods are contested or do not simply convince that incinerators cause public health impacts.

Government regulators assure the general public that MSW incinerators do not endanger public health safety because it is being warranted they adhere to the prescribed safety standards. Even so, concerns still exist and they refer to the undiscovered potential effects of the combustion by-products and how they interact with the living organisms, especially because the pollutants bio-accumulate and can cause long-term effects and over a wider geographical region. It is argued in this context that the Precautionary Principle found in national and international law, which stipulates that precautionary measures should be taken if there are uncertainties about an activity producing environmental and public health risks, should be applied as the safeness of the activity should be firstly demonstrated by the proponents, and the burden of proof should not fall onto the opponents[57].

The following air emissions are associated with incineration facilities: metals (mercury, lead and cadmium), organics (dioxins and furans), acid gases (sulphur dioxide and hydrogen chloride), particulates (dust and grit), nitrogen oxides and carbon monoxide. People can be exposed to these toxic emissions in a number of ways: inhalation of contaminated air, direct skin contact with the contaminated soil or dust, and ingestion of foods that were grown in an environment polluted with these substances. The ash resulted from waste combustion processing contains varying levels of toxic chemicals and is usually disposed of in landfills.

[57] Thomson & Anthony (2008)

Research shows that the metals and organic compounds from the landfilled ash can leach and potentially contaminate the soil and the ground water[58]. Nonetheless, the incinerator bottom ash can be further processed and utilised as aggregate replacement in base road construction, bulk fill, concrete block manufacture or concrete grouting[59].

The safety levels of an incineration plant can be jeopardised if the concentration of these toxic chemicals is above the established limits, the environmental controls are not properly implemented, the height of the emissions stack is not appropriate, if it is located too close to urban/residential area and in unfavourable weather conditions. While it has been argued that siting a WtE plant close to the source of waste (urban areas) is desirable as it reduces waste transportation costs, but also is able to provide additional important benefits such as district heating if the infrastructure is in place; studies have shown that locating WtE plants close to urban areas is not actually very safe since the discharged pollutants will predominantly fall in the surrounding area of the plant. Accordingly, isolated areas or industrial sites seem to be safer options for minimising contamination[60].

Criticisms of waste combustion also relate to the actual effectiveness of modern emissions abatement procedures and the inconsistency of monitoring plant operation to the highest standards. Modern plants are equipped with air emissions control technologies that can effectively remove the substances of concern. The technologies available to control emissions range from fabric filters, electrostatic precipitators to scrubbers. The best air pollution control system includes dry scrubbing that neutralises acids followed by a baghouse that filters emissions of metals and organic compounds. These technologies are useful as long as the combustion plants are properly operated and emissions controlled, and in many modern facilities computer control systems are utilised to achieve this. The cost implications of using the newest technologies that improve safeness are not negligible. This is a significant adoption barrier faced by the industry in the developing countries, along with the lack of trained personnel to successfully handle such a complex and daunting process[61].

Advanced thermal technologies are considered to be much safer in terms of emissions control and toxicity of dry residue. Gasification processes do not produce ash and the substances contained in the residue are environmentally benign, while the resulting syngas is a useful fuel that substitutes fossil fuels and reduces greenhouse gas emissions.

[58] UNEP
[59] WRAP (2012)
[60] UNEP ibid
[61] UNEP ibid

4. ENVIRONMENTAL IMPACTS

The environmental impacts of MSW management have been studied extensively around the world. The studies focused on the environmental performance of several methods of MSW treatment such as recycling, landfilling, incineration and anaerobic digestion. Several research papers that looked the optimal combination of MSW management in cities (for example London - Al-Salem et al., 2014, Liège - Belboom et al., 2013, Rome - Cherubini et al., 2009, Macau - Song et al., 2013, Irkutsk - Tulokhonova and Ulanova, 2013 and Seoul - Yi et al., 2011), draw similar recommendations that landfilling has the severe environmental impacts and should be minimised, recycling should be encouraged and implemented as far as possible, and energy recovery from high calorific residual waste should be maximised[62].

LAND USE

Before a WtE plant is built, an assessment of how much land is needed for operation will be conducted, as different technologies will have different land requirements. WtE plants allocate land for feedstock, waste reception, processing requirements, storage requirements and other ancillary equipment. In addition, more land could be used for depositing bottom ash and flue residues at the production site or in a landfill. The outputs of the process (heat, electricity or steam) could also require space for connecting to, for instance, heat users, electricity sub-station or local electricity distributor[63]. Table 15 below exemplifies the land area required for the building footprint and for the entire site (including supporting site infrastructure) for several gasification plants in the United Kingdom.

TABLE 15: SIZE AND LAND TAKE FOR SELECTED GASIFICATION PLANTS IN THE UK

Gasification Plants	Capacity (tonnes per annum)	Buildings Area	Total Land take	Indicative Stack Height
Avonmouth, Bristol	100,000 tpa	14,850 m^2	65,000 m^2	25m
Peterborough	650,000 tpa	43,776 m^2	137,600 m^2	49m

[62] Jeswani & Azapagic (2016)
[63] WRAP (2012)

Sheepbridge, Chesterfield	60,000 tpa	6,806.25 m^2	45,000 m^2	21m
Sinfin Lane, Derby	190,000 tpa	10,195 m^2 (of which 3,403 m^2 for ATT facility)	34,000 m^2	55m
Desborough, Northants	96,000 tpa	4,782 m^2	16,800 m^2	53m

Source: Defra (2013[64])

Finding a suitable location for a WtE plant is not always that easy and every project will take into consideration different factors. For example, some plants are located in proximity of the source of waste - an urban area, for economic reasons; while others are sited in land-use zones dedicated to medium or heavy industry, thus lowering the likelihood of pollution, noise, dust and odour in residential areas[65].

WtE plants reduce the volume of processed waste up to 90%, effectively preventing the expansion of landfills. The decline in available space for landfilling is an increasing issue in many countries around the world, making WtE technologies a solution to this pressing concern of increasing waste streams and reduced space for disposal. The land saved could successfully be used for housing, other economically productive activities or just left unutilised for nature conservation.

The environmental impact of WtE installations is not strictly proportional to treatment capacity, as shown by a 2009 study[66]. The scale of the facility is not as significant in this respect as the qualitative aspects of the MSW.

WATER USE

MSW incinerators use water in boilers and for other processes such as cleansing, slag cooling, flue gas scrubbers and staff sanitary purposes. The water used for slag cooling does not necessarily have to be sanitised, so polluted river water or from other sources can be used. The water consumption for a state-of-the-art slag extractor is on average between 0.05 to 0.01 m^3/tonne. Water is also required when flue gas scrubbers or semi-dry reactors are present, and it should contain a minimum solid content, so lime can be diluted in it and sprayed through nozzles into the flue gas stream. Water consumption will differ according

[64] Defra (2013) Advanced Thermal Treatment of Municipal Solid Waste
[65] World Bank (1999)
[66] Rada, et al. (2009)

to the technology utilised, so the semi-dry absorption process, which does not generate waste water, has an average of 0.1 m^3/tonne, while the wet process will range from 0.25 to 0.4 m^3/tonne, which produces between 0.07 to 0.15 m^3 waste water per tonne.

The water discharged from the wet process usually contains high levels of chloride and soluble heavy metals; from which cadmium is the most problematic as it has emissions limits. The variation of elements found in discharged water will depend on the initial composition of the waste feed. In addition to the water discharged from the processes at the incineration plant, there will also be cleaning water and storm water released in the area, which will most likely be contaminated with waste residues and contain high levels of organic compounds[67]. Any wash down waters or liquid within the waste is managed using a drainage system on site.

The enclosed nature of the new WtE facilities significantly reduces the impact on the water environment.

EMISSIONS

WtE can contribute to global climate change mitigation. The most effective utilisation of WtE processes can result in greenhouse gas emission reductions in three main ways. Firstly, residual waste that is sent to landfills to decompose will release significant amounts of CH_4 and CO_2, and WtE technologies can capture these gases for energy production and process the waste in a more efficient and environmentally friendly manner. Secondly, by using the energy generated by WtE plants there will be less demand for energy from fossil fuel plants, hence less production and subsequent GHG emissions. Thirdly, there is a possibility to recover ferrous and non-ferrous metals when processing waste for energy, reducing thus the demand for such primary materials and avoid emissions from extracting and treating raw materials[68].A state-of-the art WtE plant can produce carbon emission savings in the range of 100 to 350 kg CO_2 equivalent per tonne of waste processed depending on the waste composition, amount of heat and electricity supplied and country energy substitution mix. However, even greater savings (in the rage of 200 to 800 kg CO_2 per tonne of waste) will be realised if WtE replaces landfilling[69].

The environmental impact of different WtE technologies is an important criterion when it comes to assessing the best WtE strategy, but most of all it is important to compare the sustainability of WtE with that of burning fossil fuels and also of waste landfilling. Both gas phase and solid phase emissions should be taken into account. A comparison between coal fired power plants and WtE plants is considered. These two energy generation technologies produce many similar regulated constituents, with comparable emission

[67] Bank ibid
[68] UNEP (2010)
[69] CEWEP (2012)

levels. Table 16 below compares the average emissions from MSW incineration and coal combustion in the United States.

TABLE 16: EMISSIONS FACTORS (G/KWH) FROM MSW INCINERATION AND COAL COMBUSTION IN THE UNITED STATES

	MSW Incineration	Coal combustion
Carbon dioxide (CO_2)	1355.33	1020.13
Sulphur dioxide (SO_2)	0.36	5.90
Nitrogen oxides (NO_x)	2.45	2.72

Source: Wilson, Williams, Liss, & Wilson (2013)

However, in order to complete this comparison, it must be kept in mind that there are considerable additional emissions for mining, cleaning and transporting coal to the power plant.

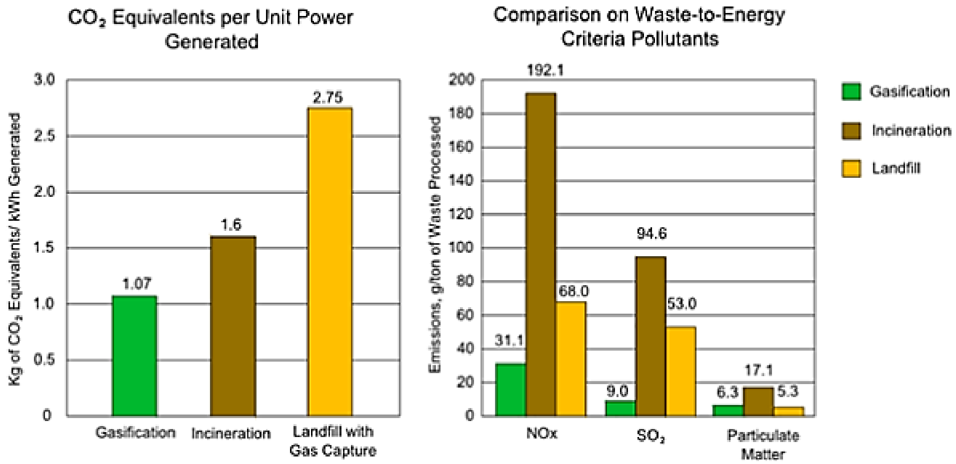
Similar considerations can be made as well for particulate emissions, which have been of great concern especially for incineration plants – i.e. dioxin and furan emission levels. To reduce particulate and gas phase emissions, both coal and incineration plants have adopted a series of process units for cleaning the flue gas stream, and this has led to a significant improvement in terms of environmental sustainability. Today, incineration plants are no longer significant sources of dioxins and furans. This is because of the implementation of governmental regulations on emission control strategies, which have led to a reduction of total annual incineration-related dioxin emissions from 10,000 grams in 1987 to 10 grams in 2013, a reduction of 99.9%[70].

As can be seen in Figure 15, emissions from WtE incineration and alternative WtE technologies (gasification and landfill with gas capture) are compared to each other. Gasification of waste produces reduced emissions per unit of generated power if compared to both incineration and landfilling. If focusing on the amount of pollutant emissions per unit

[70] United States Environmental Protection Agency

of treated waste, gasification is also the preferred option, while incineration is the most harmful.

FIGURE 15: COMPARISON OF CO_2, NO_X, SO_2 AND PARTICULATE EMISSIONS PER KWH GENERATED BY DIFFERENT WTE TECHNOLOGIES



Source: Riera & Wilson (2015)

As shown in Table 17, regarding particulates and gas phase emissions, incineration is often the most harmful technology in this field. This and other similar findings, along with a growing concern over harmful energy related emissions, have led to a fast development of alternative WtE technologies, which will likely influence the future market and change the way energy recovery from waste is done.

TABLE 17: COMPARISON OF PARTICULATE AND GAS PHASE EMISSIONS FOR DIFFERENT WTE TECHNOLOGIES

	Incineration	Pyrolysis	Plasma Arc Gasification	Aid Fed Gasification (PRM)	Anaerobic Digestion / Co-Gen	Anaerobic Digestion Gasification
Lifecycle CO_2/kWh	14-35				11	11-14
SO_x (mg/m^3)	1-40	35	26	1.2		
NO_x (mg/m^3)	40-100	77-139	150	26		

Particulates	1-20	5.75	12.8	0.018		
Ash (% of fuel mass)	5-10	in char	2-4	4-5		

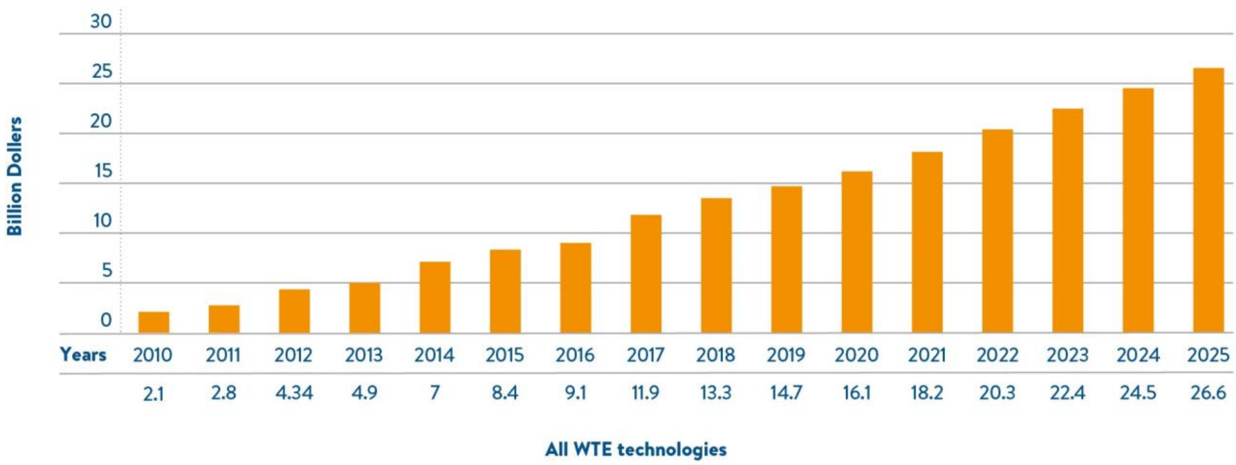
Source: Wilson, Williams, Liss, & Wilson (2013)

5. OUTLOOK

SHORT AND MEDIUM TERM

The global market is expected to maintain its steady growth to 2023, when it is estimated it would be worth US$40 billion, growing at a CAGR of over 5.5% from 2016 to 2023.[71] Figure 16 below shows that globally all WtE technologies will grow significantly even in conservative forecasts up to 2025.

FIGURE 16: GROWTH OF ALL WTE TECHNOLOGIES GLOBALLY WITH A CONSERVATIVE FORECAST UP TO 2025



Source: Ouda & Raza (2014)

Biological WtE technologies will experience faster growth at an average of 9.7% per annum, as new technologies (e.g. anaerobic digestion) become commercially viable and penetrate the market. From a regional perspective, the Asia-Pacific region will register the fastest growth over this period (CAGR of 7.5%), driven by increasing waste generation and government initiatives in China and India; and higher technology penetration in Japan. Growth in the Asia-Pacific region will also be characterised by the implementation of low cost technologies indigenously designed to specifically treat local waste, leading to a very competitive market.

[71] http://www.mynewsdesk.com/us/global-market-insights/pressreleases/waste-to-energy-wte-market-size-industry-outlook-potential-report-regional-analysis-2016-2023-1374171

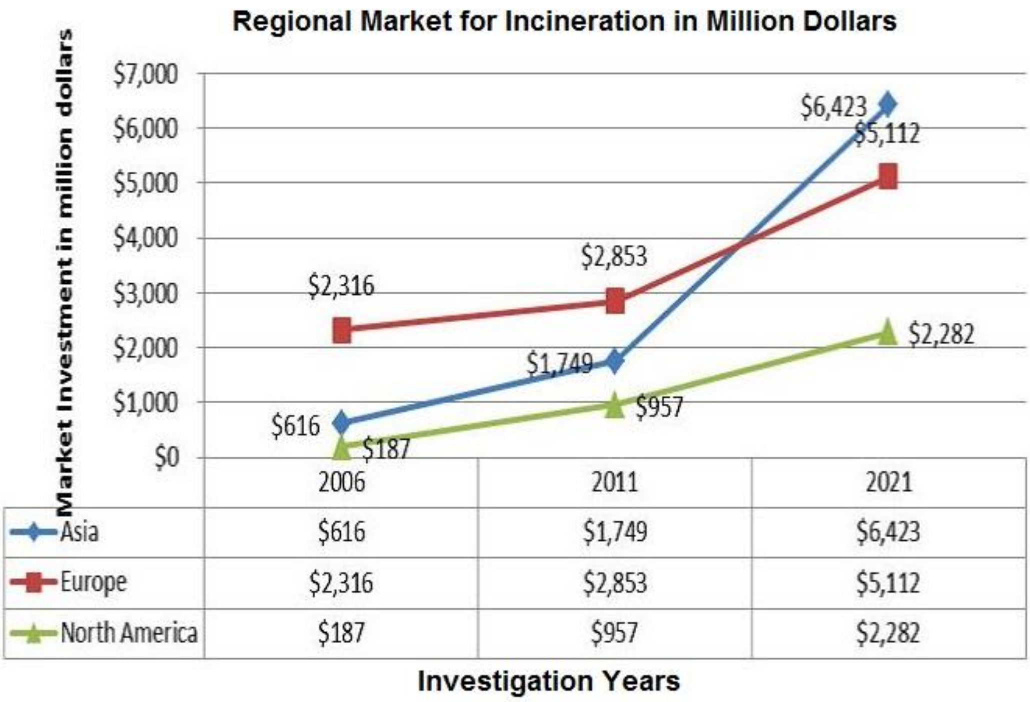
WtE market will continue to develop globally as governments will impose supportive regulation with subsidies and tax benefits. The need to increase the share of renewable energy and reduce GHG emissions, along with raising environmental consciousness to protect the environment from polluting and unsustainable practices such as landfilling will have a positive impact on WtE market development. In addition, as waste generation will grow, there will be enough space in the market for new entrants.

One of the biggest barriers to market development will be the high technology costs in comparison with landfilling, which is the most financially-effective way of waste disposal. The growth of the market and future technological advancements will most likely drive the costs down for WtE technologies, making them affordable in developing countries as well. Further research into increasing the energy efficiency of the plants, along with treating outputs from pollutants such as desulfurisation of flue gas, is expected to benefit the market growth. Bio-chemical treatments of waste are expected to contribute significantly to the market development, especially in developing countries[72].

Incineration is the dominant WtE technology globally and this trend is likely to continue owing to relatively low technology costs, market maturity and high efficiency (of about 27%). Plus, incineration is suitable in both urban and rural areas and takes in all types of waste. Figure 17 below shows the incineration market trend in Asia, Europe and North America. It can be observed that Asia is going to continue investing heavily in waste combustion with energy recovery, followed by Europe and North America, which has a much slower ascendant trend. Other thermal technologies such as Gasification and Pyrolysis are more efficient, score better in environmental impacts but have still high capital costs, and fit best countries with available capital and limited land resources, like the case of Japan.

[72] Hexa Research (2016)

FIGURE 17: MARKET INVESTMENT FOR INCINERATION IN ASIA, EUROPE AND NORTH AMERICA



	2006	2011	2021
Asia	$616	$1,749	$6,423
Europe	$2,316	$2,853	$5,112
North America	$187	$957	$2,282

Source: Ouda & Raza (2014)

Governments around the world will increasingly adopt better MSW management practices, which include treating residual waste with various WtE technologies as it is a viable option for disposal of MSW and energy generation. There are many factors that will influence the choice of technology and every region will have to properly assess its specific context to implement the most reasonable solution. The WtE sector is very complex, fragmented in terms of policy and regulation and has a huge untapped potential. Both international and regional orchestrated efforts are necessary for the WtE market to be able to spread, benefitting thus the waste management and energy sectors.

6. GLOBAL TABLE

TABLE 18: RENEWABLE MUNICIPAL WASTE[73] (MW) 2015 DATA

Country	Electrical Generating Capacity (MW) in 2015 IRENA (2016)	Electricity Generation (GWh) from RMW in 2014 IRENA (2016)	Municipal Solid Waste Generation Per Capita kg/year in 2014 Eurostat (2016)
Austria	539	285	565
Azerbaijan	37	174	-
Belgium	247	810	435
Canada	34	89	850*
Chinese Taipei	629	1 596	-
Czech Republic	45	88	310
Denmark	325	885	759
Estonia	210	-	357
Finland	-	441	482
France	872	1 824	511
Germany	1 888	6 069	618
Hungary	22	137	385
Iceland	-	-	345

[73] Municipal Solid Waste is generally accepted as a renewable energy source.

Country	Electrical Generating Capacity (MW) in 2015 IRENA (2016)	Electricity Generation (GWh) from RMW in 2014 IRENA (2016)	Municipal Solid Waste Generation Per Capita kg/year in 2014 Eurostat (2016)
India	274	1 090	124*
Indonesia	7	32	190*
Ireland	17	68	586
Israel	6	14	774*
Italy	826	2 370	488
Japan	1 501	6 574	624*
Korea Rep	184	564	-
Latvia	-	-	281
Lithuania	10	29	433
Luxembourg	17	34	616
Malaysia	16	17	555
Martinique	4	23	-
Netherlands	649	1 909	527
Norway	77	176	423
Poland	-	-	272
Portugal	77	240	453
Qatar	25	110	485*

Country	Electrical Generating Capacity (MW) in 2015 IRENA (2016)	Electricity Generation (GWh) from RMW in 2014 IRENA (2016)	Municipal Solid Waste Generation Per Capita kg/year in 2014 Eurostat (2016)
Singapore	128	963	544*
Slovakia	11	22	321
Slovenia	-	-	414
Spain	251	686	435
Sweden	459	1 626	438
Switzerland	398	1 102	730
Thailand	75	201	624*
United Kingdom	781	1 422	482
United States of America (USA)	2 254	8 461	942*
Uruguay	1	-	40*
World	**12 912**	**40 131**	-

Source: IRENA Capacity Statistics 2016, IRENA Renewable Energy Statistics 2016, Eurostat Press Release of 22 March 2016

Note: Numbers are approximated, with for instance figures between 1 and 1.5 shown as 1, and between 1.5 and 2, shown as 2.
*Data collected from 2012 World Bank Report, Urban development - What a Waste: A global review of solid waste management.
Please note that an accurate comparison between countries in terms of waste generation cannot be easily realised, because waste data is registered differently and countries use different calculations for establishing the quantity of waste generated.

LIST OF TABLES AND FIGURES

FIGURES

TABLES

REFERENCES

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