

# Waste-to-Materials – the longterm option

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# Chapter 1

## Waste-to-Materials – the longterm option

Philip Nuss<sup>1</sup>, Stefan Bringezu<sup>2</sup>, Kevin H Gardner<sup>1</sup>.

**Abstract** Managing solid waste is one of the biggest challenges in urban areas around the world. Technologically advanced economies generate vast amounts of organic waste materials, many of which are disposed to landfills. In the future, efficient use of carbon containing waste and all other waste materials has to be increased to reduce the need for virgin raw materials acquisition, including biomass, and reduce carbon being emitted to the atmosphere therefore mitigating climate change. At end-of-life, carbon-containing waste should not only be treated for energy recovery (e.g. via incineration) but technologies should be applied to recycle the carbon for use as material feedstocks. Thermochemical and biochemical conversion technologies offer the option to utilize organic waste for the production of chemical feedstock and subsequent polymers. The routes towards synthetic materials allow a more closed cycle of materials and can help to reduce dependence on either fossil or biobased raw materials. This chapter summarizes carbon-recycling routes available and investigates how in the long-term they could be applied to enhance waste management in both industrial countries as well as developing and emerging economies. We conclude with a case study looking at the system-wide global warming potential (GWP) and cumulative energy demand (CED) of producing high-density polyethylene (HDPE) from organic waste feedstock via gasification followed by Fischer-Tropsch synthesis (FTS). Results of the analysis indicate that the use of organic waste feedstock is beneficial if greenhouse gas (GHG) emissions associated with landfill diversion are considered.

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## **1.1 Evolution of Waste Management Practices and the Socio-Industrial Metabolism**

### ***1.1.1 Waste Generation and Management in a Development Perspective***

Since prehistoric times, human activities generated waste materials that were discarded because they were considered of low-value or useless. In the early days, the disposal of wastes did not pose a significant problem, as the population was small and land for the assimilation of wastes was widely available. However, as the human population grew and began to settle in villages and communities, the accumulation of waste became a rogue consequence of life (1). Since then, the turnover of materials has increased dramatically. This is not only due to global population growth but also due to the enormous growth of goods and assets used per person, in particular in affluent countries. Thus, along with the benefits of technology have also come the problems of disposal of resultant wastes.

Today, approximately 745 kg of municipal solid waste (MSW) are produced per capita per year in the United States (2) and an average of 522 kg MSW in the EU-27 (3). Modern man consumes between 30 to 75 tons of material per person per year in their companies and households (4). Of the materials consumed, an average of 90% of all biomass inputs and more than 90% of the non-renewable materials used are wasted on the way to making products available to the end-user (5). Although materials are used more and more efficiently, there are no indications that overall material consumption will decline (6) and as a result it is expected that large amounts of waste will continue to be generated in the future (7). Although in developing countries the quantity of solid waste generated in urban areas is low when compared to industrialized countries, waste management still remains inadequate (8). Rapid economic growth and rise in community living standard in many of the low- or middle-income countries are likely to accelerate MSW generation as well as the complexity and variety in terms of substances present.

Managing these solid waste streams well and affordably is one of the key challenges of the 21<sup>st</sup> century (9). Traditionally, municipal solid waste management encompasses the functions of collection, transport, resource recovery, recycling, and treatment. The primary goal of MSW management is to protect the health of the population, promote environmental quality, develop sustainability, and provide support to economic productivity (8). In addition, climate change has drawn attention to the diversion of biodegradable municipal solid waste (BMSW), such as kitchen and garden waste, from landfills because it has the potential to form methane (a powerful greenhouse gas) under anaerobic conditions. According to the

U.S. Environmental Protection Agency (EPA) the four basic options for integrated solid waste management include: (1) source reduction, including reuse, (2) recycling and composting, (3) combustion (waste-to-energy facilities), and (4) landfills (10). Examples from e.g. Denmark and Japan suggest that a sustainable waste management system furthermore consists of a stable mixture of technologies and institutions which work flexibly under a defined policy umbrella (9). Such sustainable waste management systems are designed to mimic an ecosystem that is robust and resilient. Taking a systems-perspective can help to e.g. determine whether materials currently regarded as wastes in one industrial sector could be viewed as raw materials by another sector.

### ***1.1.2 Future Perspectives for Sustainable Waste Management***

Ecosystems provide the best example of a system that works in a sustainable fashion (11). One of the central principles in industrial ecology is the vision that industrial systems can use materials extracted and metabolized in a cyclical manner, driven by renewable energy which is used in a cascading manner (12). One important measure relates to the systematic reuse of waste products in order to minimize the need to extract virgin raw materials and deplete environmental services (13). However, to date recovery rates for materials such as metals, plastics, paper etc. from the municipal waste stream vary widely, even among industrialized countries. For example, in Germany in 2007 a total of 25% of all MSW generated was disposed to landfills and incinerators (14), while in the United States a total of 67% of all MSW generated in 2008 was discarded (2,15). Furthermore, the EU landfill directive sets targets to progressively reduce the amount of BMSW disposed to landfills among the EU member states (including Germany), whereas in the United States large amounts of organic waste are sent to landfills. This happens despite the fact that organic waste, being rich in carbon, could serve increasingly as feedstock for thermal and biological processes recovering the carbon for further use as chemical feedstock ('carbon recycling').

The concept of *carbon recycling* is that, instead of releasing the carbon stored in biowaste into the atmosphere by applying conventional waste management practices such as incineration (for heat) or anaerobic digestion and landfilling (for biogas/landfill gas), the carbon inherent in the organic waste should be seen as a valuable feedstock resource (16). Instead of carbon-capture and storage, which generally occurs at the beginning of the resource flows (e.g. at oil extraction sites to reduce fossil GHG emissions), the principle of carbon-capture and reuse could be further developed and applied throughout the whole socio-industrial metabolism. Specifically, technologies such as gasification, which allows the generation of a syngas, or anaerobic digestion, for the generation of an upgraded biogas (me-

thane), could be applied<sup>3</sup>. Both syngas and biogas can then serve as feed e.g. for the Fischer-Tropsch synthesis (FTS) to produce base compounds such as Fischer-Tropsch (FT)-naphtha and a number of subsequent chemical products and fuels. In addition, hydrolysis followed by fermentation can be applied to generate a variety of different base chemicals.

When fuels (e.g. FT-diesel, methanol, ethanol, etc.) are produced from organic waste and oxidized by use in combustion engines, the carbon (originally captured in the waste feedstock) is emitted back to the atmosphere. Assuming that the system-wide environmental burdens along this process route are lower than those of conventional fossil-based fuels production routes, this process route would lead to a mitigation of environmental burdens. However, this route of using carbon as fuel is still a linear process through the socio-industrial system which depends on significant amounts of waste feedstock being available (16).

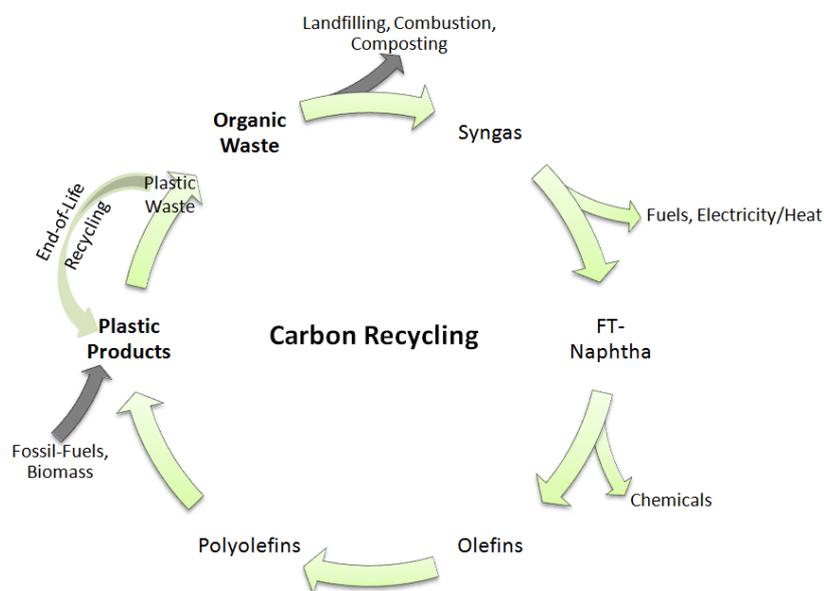
If, in contrast, synthetic materials for the production of plastics could be synthesized, then the carbon would be kept longer in the use phase and add to the stock of durable goods in the technosphere. The plastic products could potentially be recycled at end-of-life to provide feedstock for either energy generation or as feedstock for the production of syngas in a cascading use scheme. Fig.1 exemplifies the concept of carbon recycling, making use of organic waste as feedstock for polyolefins production for the example of Fischer-Tropsch synthesis.

From an environmental perspective the use of waste would be advantageous as, in comparison to virgin greenwood biomass, it has no direct land-use requirement and collection and processing systems are oftentimes already in place (18). In addition, thermal treatment (i.e. gasification) has the further advantage of contributing to volume reduction, waste disinfection, and concentration of certain toxic elements (e.g. cadmium) in the gasification ash and slag produced<sup>4</sup>. A comprehensive systems analysis is required to assess the life-cycle wide performance of carbon recycling compared to conventional systems of waste management.

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<sup>3</sup> In addition, in the future other carbon recycling technologies such as the synthetic tree air-capture unit, developed by Klaus Lackner of the Earth Institute at Columbia University, that stands in the open and captures CO<sub>2</sub> on its collector surfaces (“leaves”) comprised of anionic resin (17), may serve as source of carbon for chemicals feedstock synthesis.

<sup>4</sup> The removal of hazardous substances from the waste via thermal treatment leads to an ash or slag rich in hazardous substances, potentially enabling efficient recycling of metals from the waste stream in the future (7).



**Fig.1** Carbon recycling: making use of organic waste via the Fischer-Tropsch synthesis (FTS). Organic waste that could not be recovered via conventional waste recovery systems is gasified and transformed into a FT-naphtha (as well as by-products such as FT-diesel and electricity/heat). FT-naphtha is then transformed into olefins via conventional steam cracking. Polyolefins are generated via polymerization and used for the production of plastic products. At end-of-life these products can either be disassembled and the plastic parts be reused (preferred option if less energy and resource intensive than subsequent FTS) or the carbon and energy recovered via gasification producing a syngas and therefore closing the cycle.

From an environmental perspective the use of waste would be advantageous as, in comparison to virgin greenwood biomass, it has no direct land-use requirement and collection and processing systems are oftentimes already in place (18). In addition, thermal treatment (i.e. gasification) has the further advantage of contributing to volume reduction, waste disinfection, and concentration of certain toxic elements (e.g. cadmium) in the gasification ash and slag produced<sup>5</sup>. A comprehensive systems analysis is required to assess the life-cycle wide performance of carbon recycling compared to conventional systems of waste management.

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## 1.2 Carbon recycling and increased resource efficiency

### 1.2.1 Exemplary routes of carbon recycling

Organic waste refers to all carbonaceous waste fractions that can potentially serve as feedstock for the thermochemical and biochemical platforms. These include:

- Biodegradable municipal solid waste (BMSW);
- Municipal plastic waste;
- Construction & demolition (C&D) derived biomass; and
- Liquid waste (e.g. sewage sludge).

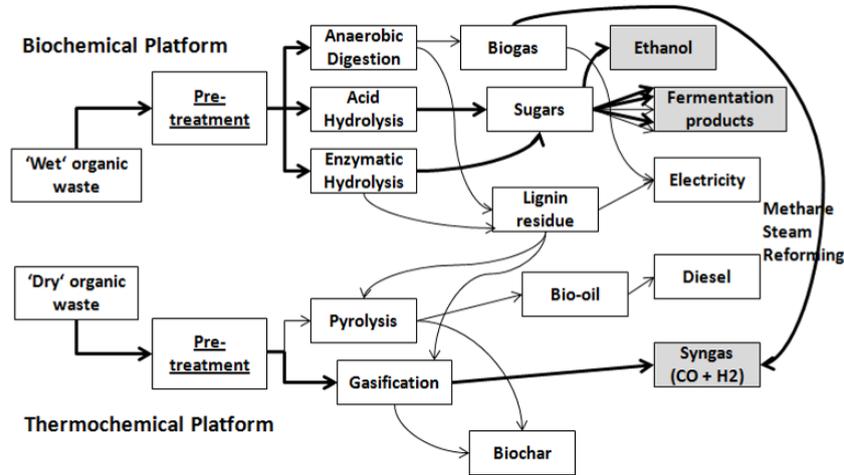
*BMSW* includes all waste fractions of biological origin such as food wastes, paper, cardboard, yard wastes, and bulky wood waste. Of this the *cellulose and hemicelluloses fractions* can serve as feedstock for hydrolysis with fermentation or anaerobic digestion (kitchen organic waste, green organic waste and paper and cardboard). *Plastic waste* includes durable goods made from fossil-based<sup>6</sup> plastics such as PE, PP, PET, etc. *C&D derived biomass* originates from new construction sites and repairs and consists of treated and untreated wood fractions. *Organic liquid wastes* include municipal sludges such as sewage sludge and animal wastes that can be treated via anaerobic digestion or can be gasified after drying. In addition, industrial organic waste feedstock may be of interest as it often times is more homogeneous than waste from municipal sources.

Organic waste can serve as feedstock for the production of transportation fuels, chemical feedstock and bio-energy using biochemical and thermochemical conversion routes. Current research with regards to biorefineries focuses mainly on the utilization of lignocellulosic materials, originating from agriculture and forestry, as second generation feedstock for the production of bio-fuels and chemicals. Interest in the use of organic waste residues as feedstock is growing. Biochemical processes will either employ anaerobic digestion or hydrolytic mechanisms to break apart the structural polysaccharides (lignocellulose) of the biomass. Alternatively thermochemical procedures can be used to dehydrate and volatilize the biomass feedstock. Research in bio-refining is proceeding quickly and commercial

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<sup>6</sup> In the beginning the thermochemical platform would, amongst other feedstocks, utilize conventional fossil-based plastics as feedstock for the production of syngas and subsequent plastics via the methanol to olefins (MTO) or Fischer Tropsch synthesis (FTS). However, as this platform is continuously applied to recycle plastic waste by gasification and to produce new plastics from them, this implies that the feedstock origin will slowly shift from fossil- to waste based plastics (assuming that fossil-based feedstocks will become increasingly scarce over the course of the next decades). At the same time those plastics will slowly fade out that are less appropriate as feedstock or end-product of the recycling pathway.

facilities are expected in the near-future (19). Fig.2 provides an overview of the conversion technologies available for the treatment of organic waste. The bold arrows indicate pathways of interest for the synthesis of industrial feedstocks including plastic polymers.

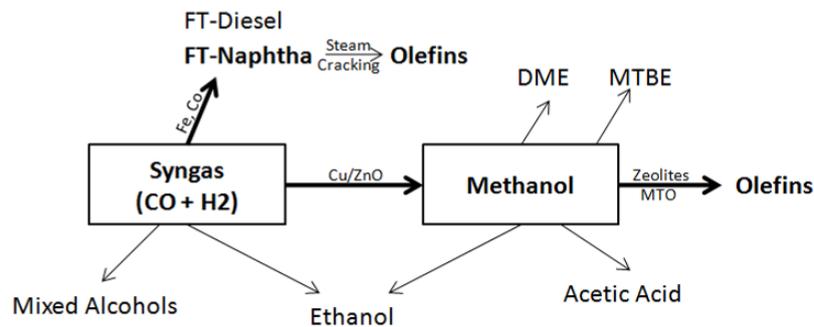


**Fig.2** The various conversion technologies possible for the treatment of organic waste (Source: compilation adapted from (19)). Organic waste with high water content is treated in the biochemical platform in which either anaerobic digestion or acid/enzymatic hydrolysis are applied. Anaerobic digestion produces a biogas consisting mainly of  $\text{CH}_4$  and  $\text{CO}_2$  that can subsequently be converted into a syngas. Hydrolysis produces sugars which can be fermented into a variety of different base chemicals. Thermochemical processes apply gasification or pyrolysis of dry organic waste to derive at a syngas which serves as intermediate for the production of a potentially large number of chemicals (see Fig.3). Please note that thermochemical processes, in contrast to anaerobic digestion and hydrolysis with fermentation, are able to utilize a large number of dry organic feedstock sources, including BMSW, plastic waste and C&D waste. Arrows in bold indicate routes of interest for the production of basic chemicals and polymers that would allow cascading use and carbon recycling.

Generally, the thermochemical platform, using gasification, will be superior to the biochemical platform if an organic waste fraction with low water content is used, whereas biochemical conversion generally works better if biomass with high water content is utilized (20).

### 1.2.1.1 Thermochemical platform ('dry' carbon recovery)

Thermochemical conversion for the production of fuels and chemicals uses either *pyrolysis* or *gasification*. Pyrolysis is the thermal treatment of biomass in the absence of oxygen and results in the production of bio-oil, gases, or bio-char. Gasification occurs at higher temperatures ( $> 1000^{\circ}\text{C}$ ) and in less oxygen-restricted conditions than pyrolysis and leads to the formation of a synthesis gas (syngas) rich in hydrogen and carbon monoxide. The intermediate products of both processes have the potential as a feedstock for fuel and chemical synthesis via various catalytic pathways (e.g. Fischer Tropsch synthesis). Based on the current stage of development, gasification shows a higher potential for near-term deployment, whereas pyrolysis will be important in meeting longer-term goals with regards to fuels and chemicals production (21).



**Fig.3** The potential chemicals from syngas and some of the catalysts involved (Source: compilation adapted from (22)). Syngas serves as industrial feedstock for the production of a variety of base chemicals. With respect to durable goods for cascading use, FTS and Methanol-to-Olefins (MTO) routes are of particular interest. Both allow the production of olefins which can subsequently be polymerized to derive at polyolefins.

### 1.2.1.2 Biochemical platform ('wet' carbon recovery)

Biochemical conversion either uses *acids* or *enzymes* to catalyze the conversion of the carbohydrate portion of the biomass (hemicelluloses and cellulose) into intermediate sugars that are then fermented to ethanol and other products. The remaining lignin residue that cannot be processed via the biochemical platform can be used for heat and power production, or alternatively used in the thermochemical conversion process to produce additional fuels and chemicals.

*Anaerobic digestion* is a fermentation technique that results in a biogas containing mostly of  $\text{CH}_4$  and  $\text{CO}_2$  but generally carrying impurities such as  $\text{H}_2\text{S}$ ,  $\text{H}_2\text{O}$ ,  $\text{NH}_3$ , siloxane, and particulate matter. Anaerobic digestion is the principal process occurring in landfills (producing what is typically referred to as Land Fill Gas, or LFG) and occurs naturally in marshes, wetlands and manure lagoons (23).  $\text{CH}_4$  for energy production can be obtained by upgrading the biogas. Syngas can be produced by steam reforming the upgraded syngas. Similar to the subsequent

steps of the thermochemical platform, syngas can then be utilized for e.g. the production of methanol or FT Naphtha (Fig.3). Direct olefin production from upgraded biogas is potentially possible via oxidative coupling (Fig.2).

### ***1.2.2 Chemicals and polymer production pathways: What is potentially possible?***

Both thermochemical and biochemical conversion platforms allow the production of a variety of base chemicals and subsequent plastic polymers from organic waste. The reason for looking at base chemicals for the production of synthetic materials rather than fuels is the possibility of a more efficient cascading use in which a durable good (plastic polymer) is produced first and its energy content recovered at end-of-life. Gasification and fermentation both seem to be complementary to each other in terms of polymers they can produce. However, gasification has the clear advantage to be able to utilize a broader variety of waste feedstock (not only lignocellulosic waste but also plastics and C&D waste) and seems to have the advantage that possible toxic substances can be extracted directly from the syngas rather than the organic waste feedstock.

From a traditional base utilizing the natural complex macromolecules of e.g. starch and cellulose as raw materials for the production of biopolymers, the polymer industry is turning attention towards synthetic polymers based on renewable raw materials. Key polymer building blocks include e.g. alcohols such as methanol (C1), ethanol (C2) for the production of polyethylene and polypropylene polymers, glycerol (C3) as a building block for the production of polyurethanes, C3 to C6 carboxylic acids (e.g. lactic acid, succinic acid, and itaconic acid) as well as aromatic aldehydes (e.g. 5-hydroxy-methyl-furfural (HMF, C6) and Fischer Tropsch Naphtha (C5-C12)). Strategies differ between replacement of conventional fossil-fuel derived plastics and the development of novel building blocks using biochemical and thermochemical conversion.

In terms of current production volume, ethylene and propylene as well as their derivatives dominate the plastics industry by feeding the polyethylene, polypropylene, ethylene oxide, styrene, polyvinylchloride, and a number of other supply chains (24,25). With a production volume of more than 150 million tons, light olefins (e.g. ethylene and propylene) are currently the most important basic petrochemicals to produce plastics, fibers and other chemicals (26). In this regard, the methanol to olefins (MTO) route, Fischer Tropsch Synthesis (FTS) towards FT-naphtha and biogas to olefins routes (either steam reforming or oxidative coupling) seem to provide interesting future pathways for olefins production from organic feedstocks. The MTO route as well as the route from methanol to acetic acid are well-established. FT-naphtha could play a key role as a base chemical, from which a variety of chemicals, including polymer building blocks, can be obtained.

### 1.2.3 MSW Feedstock Quality Issues

The quality of MSW as a feedstock for fermentation or gasification is important in terms of pre-treatment and conversion facility design. Barriers to fermentation and anaerobic digestion of MSW include the ability to effectively separate BMSW material from other wastes whereas gasification requires costly and possibly energy-intensive drying of moist feedstock as well as gas cleanup later in the process chain. Potential variations in feedstock quality and availability, as well as the cost of handling and competing uses such as recycling, compost, waste-to-energy (WTE) and landfill gas generation are further issues of concern.

The composition of MSW varies significantly among countries as well as among regions within individual countries (e.g. urban vs. rural areas). These variations are caused for example by differences in consumer habits, diet and disposal patterns and relate furthermore to the level of affluence and development of the country (27). *One of the biggest challenges faced by developers of waste conversion facilities is the heterogeneity of the feedstock.* Varying MSW composition over time<sup>7</sup> is a challenge for most conversion facilities and performance will depend on their flexibility to cope with these changes and to be able to process a number of alternative feedstocks. Methods that can be applied to deal with these issues are: on-site storage and blending, mixing and shredding of the waste, compression and baling of the input, and integration with a Materials Recovery Facility (MRF) to obtain a more homogeneous waste feedstock (27).

A number of studies on the use of MSW as raw material for the production of fuels and chemicals has been published to date (e.g. (28-43,23,44)). With respect to biochemical conversion (hydrolysis + fermentation), these studies indicate that, by optimizing BMSW pre-treatment and hydrolysis procedures, more than 85% of the waste cellulose fraction can be converted into glucose (36) which could be converted to fermentation products such as ethanol and other platform chemicals. Depending on the waste composition, pretreatment methods using dilute sulfuric acid or hydrochloric acid followed by enzymatic hydrolysis and steam and pressure pretreatment have been investigated. However, chemicals (e.g. biosurfactants and antimicrobials) present in the feedstock have the potential, if not removed, to inhibit enzymatic hydrolysis or fermentation resulting in lower yields of the intermediate-products (33). Most studies looking at fermentation of BMSW have focused on the production of ethanol as biofuels for transportation purposes. All of these studies looked at the conversion of MSW on the lab- or pilot-scale. *So far, no commercial plants applying hydrolysis followed by fermentation of the sugars are operating.*

In contrast to fermentation, *pyrolysis and gasification techniques are widely used for the processing of waste feedstock.* As of 2001, there were 110 plants op-

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<sup>7</sup> This includes variations caused by e.g. changing household patterns due to the season (e.g. more garden waste in summer); unusual events such as Christmas, holidays; etc.

erating in 22 countries processing over 5 million tons of waste per year applying gasification and/or pyrolysis (27). The majority of these efforts focus on the utilization of MSW and other dry waste fractions to recover energy in gas turbines. However, a wide range of technologies is emerging for the conversion of organic waste to biofuels. These technologies are able to use a wide variety of waste feedstocks, including C&D derived biomass as well as plastics waste, and have been proven on the commercial scale, mainly in Europe and Japan.

Similar to thermochemical technologies, anaerobic digestion (AD) of BMSW have advanced mainly in Europe but facilities were recently also built in Canada, Japan, Australia and several other countries (47). AD systems are applied in many wastewater treatment facilities for sludge degradation and stabilization and are used to treat those wastewaters prior to discharge. Some facilities are also employed at animal feeding operations to reduce the impacts of manure and to use it as a feed for energy production from biogas. Of the organic waste fraction of MSW wet BMSW such as food and yard wastes can be treated in anaerobic digesters. AD therefore represents a commercially available alternative to aerobic fermentation techniques. European technologies all use extensive pre- and post digestion processing units. These include visual manual or robotic sorting and removal of bulky or potentially harmful items, particle size reduction and separation (see (47) for further details) adding to the cost of these technologies.

*Gasification seems to be favored over biochemical conversion* due to the fact that contaminants (alkali metals, halides, sulfur gases, and tars) present in the biodegradable fraction of the waste can (in comparison to pre-sorting and steam-cleaning the biomass itself) be removed from the produced syngas before catalytic conversion (e.g Fischer-Tropsch) to the intermediate products takes place. If not removed, these contaminants can poison the noble metal catalysts. In addition, gasification utilizes both the lignin as well as the cellulose and hemicelluloses fractions of the BMSW feedstock and has the potential to utilize additional waste fractions such as plastics and C&D waste.

Among the advantages of using organic waste as a primary feedstock for biofuels and bio-materials are that unlike other lignocellulosic feedstocks, MSW has an already well-established collection system and processing infrastructure and is generally available at a negative cost. In contrast to agricultural waste and energy crops which are harvested on a seasonal basis, BMSW provides a year-long supply of feedstock for the biochemical and thermochemical platform. Since the major fraction of MSW consists of organic waste, utilization of MSW provides environmental benefits, as for instance reduction of GHG emissions (CO<sub>2</sub>, CH<sub>4</sub>) and landfill space (landfill diversion).

### ***1.2.4 Potentials for Developing and Emerging Countries***

Waste gasification, anaerobic digestion and fermentation are technologies still under development. Implementation will require significant investments and initial investors will have to carry the risk of whether they are able to successfully introduce these technologies to the market. While gasification systems may be affordable in affluent countries such as Germany or the United States, they are unlikely to be either appropriate or financially affordable in developing countries in the short-term, simply because citizens have lower incomes and are therefore not be able to pay as much for waste management and carbon recycling. A modern gasifier designed for high-heating value European wastes is likely to require additional fuel inputs to gasify a typical high-organic and relatively wet waste in a developing country. Furthermore, the costs and expertise required to operate and maintain the system in a continuous manner is likely to restrict it to a few cities with most advanced waste collection and separation systems in place in developing or transitional countries. In addition, a novel conversion technology that has not yet been introduced to e.g. the European market is a risky choice for the developing world which requires systems that are guaranteed to be reliable in collecting, treating and disposing of the waste, all year around. Therefore, we envision these technologies to be first introduced in industrialized nations and mega-cities of emerging economies with high volume generation rates of organic waste feedstock.

However, it should be pointed out that in particular the thermochemical platform has the capability of combining safe waste handling of organic waste with the production of energy, fuels and chemical feedstock. According to UN-Habitat data, significant increases in the occurrence of sickness among children living in households where (organic) waste is dumped or burned in the yard can be observed (49). Organic waste materials can pollute surface and groundwater and therefore pose a threat to the health of people who depend on these water resources for drinking water. The potential of gasification technologies to destroy harmful microorganisms at high temperatures and concentrate hazardous metals in the slag and ash could become of increasing interest for developing countries in the future. In addition, feedstock flexibility would potentially allow utilizing both, organic waste as well as virgin green wood biomass as gasification feed. Finally, operating smaller decentralized conversion facilities would allow the production of energy, fuels and chemicals without having to build large refineries and power plants.

### **1.3 Status of Knowledge: Waste as Feedstock for Thermo- and Biochemical Conversion**

#### ***1.3.1 Resource Potentials with a Focus on Developing Countries***

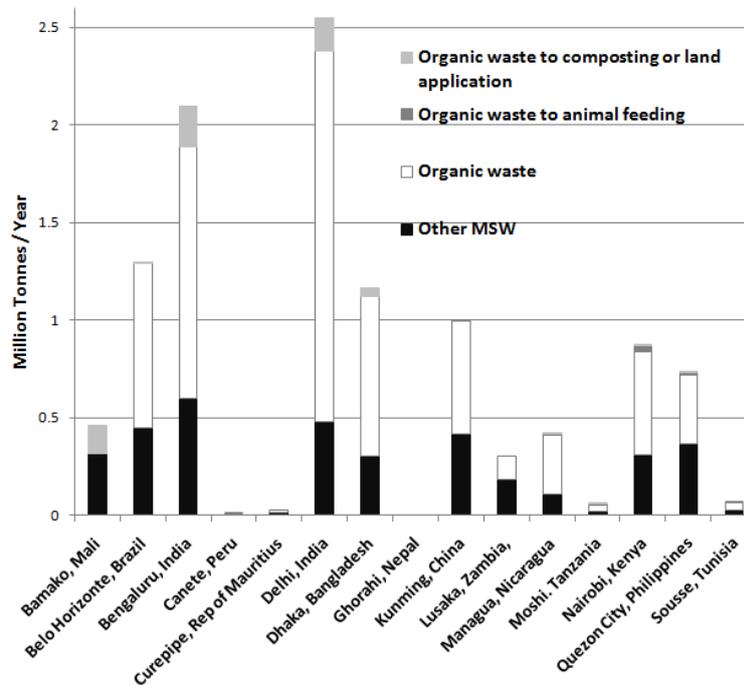
The data on solid waste generation and recovery rates in developing countries is scarce (50). Even a rough estimate of waste amounts and composition as well as recovery and recycling rates is often not possible. When data exists it is difficult to do comparisons even within a city because of inconsistencies in data recording, collection methods and seasonal variations. However, a recent overview of a number of reference cities in developing and emerging countries is given in (9). According to this study, in low gross domestic product (GDP) cities, waste density can be as high as 400 kg per cubic meter due to high fractions of wet organic waste. A comparison of all reference cities indicates that organic waste is a very large part of the waste stream in all cities investigated. The organic fraction is often between 50 and 70 weight-% of MSW in developing countries. Low- and middle-income countries were found to have relatively high percentages of organic waste (above 45 weight-%) in cities such as Cairo, Cluj, Lima, Pune, and Quezon City<sup>8</sup>.

While in industrialized countries the value of organic waste often times is due to composting or incineration and anaerobic digestion for energy production, in cities of the developing world organic waste is used mainly to feed livestock (especially swine feeding) and to generate compost for land application (9). It is important to note that the informal sector does most of the recycling related to organic waste in developing countries. This includes street pickers, dump-pickers, itinerant waste buyers and junk shops that collect and deal with the waste feedstock as long as a market for the product exists. This is, however, only partially true for organic wastes. While food waste may have a market value as animal feed, products made from compost are increasingly being replaced e.g. by chemical fertilizers.

Fig.4 shows the amounts of organic waste going to animal feeding, composting or land application in a number of cities around the world. As can be seen from the figure, still large amounts of organic waste feedstock remain unutilized. This fraction could potentially serve as feedstock for thermochemical or biochemical conversion technologies.

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<sup>8</sup> See Key Sheet II in chapter 4 of the (9) report.



**Fig.4** Destination of organic waste generated in MSW per year in a number of cities around the world (Source: compilation using data from (9)). For example, in Delhi, India, a total of 2.55 million tonnes of MSW are generated per year. Of this roughly 2.10 million tons consist of organic waste of which 8% (165,565 tonnes) is diverted to composting or land application.

### 1.3.3 Environmental Performance Evaluation: Waste-to-Chemicals

A limited number of studies looking at the life-cycle-wide environmental implication of the route MSW to fuels/chemicals have been carried out to date. These studies focus on the production of heat, electricity and fuel (51), including methanol (52), ethanol (53-55) and synthesis gas (56) from MSW. All of these products are interesting intermediates on the way to synthetic materials. Methanol could serve as base chemical for the methanol-to-olefins (MTO) route, whereas ethanol can be transformed into ethylene and subsequent polypropylenes. Syngas acts as a base chemical for a variety of routes including MTO and the FTS and can be used for the production of electricity.

These studies indicate that utilizing the organic fraction of MSW for energy recovery or material recycling may have advantages in terms of GHG emissions savings and to reduce fossil-energy consumption when compared to conventional

use including current waste management practices (e.g. landfilling and incineration) and transportation purposes to replace fossil-based petrol. Material recycling through the provision of base chemicals (syngas, methanol, and ethanol) via fermentation and gasification seems to be possible. The overall environmental performance will largely depend on the choice of assumptions made and comparisons applicable (e.g. landfilling with or without landfill gas recovery, inclusion of MSW collection and classification, etc.). Key processes and their performance will be exemplified in the following.

## 1.4 MSW Processes to High-Value Products

This section presents results from one case-study carried out on gasification routes from organic waste to chemical feedstock. We assessed the system-wide global warming potential (GWP) and cumulative energy demand (CED) associated with these routes using attributional life-cycle assessment (LCA). Data collection for the foreground system as shown in the case study below was gathered from available literature. All supplies of materials, electricity, energy carriers, services, etc. were modeled with best available background data from the ecoinvent database (57), the U.S. LCI database (58) and other published LCI data sources. SimaPro LCA software was used to calculate the life cycle inventory and carry out the impact assessment.

### 1.4.1 Case Study: Waste-to-olefins via Fischer-Tropsch Synthesis (FTS)

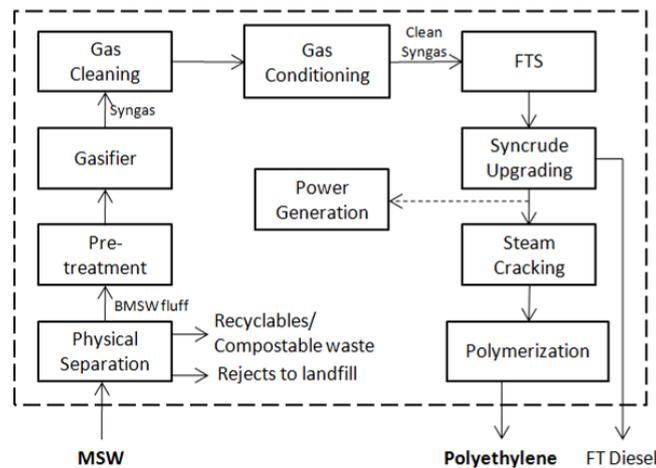
#### 1.4.1.1 Methodology

This analysis compares the use of organic waste for polyethylene (PE) production with the production process using crude oil in a conventional refinery. The goal is to estimate the life-cycle environmental burdens with regards to GWP and CED associated with the production of 1 kg of PE at the factory gate. This analysis is based primarily on U.S. waste collection practices, technological parameters and background data. Electricity inputs to the foreground system (Fig.5) are assumed to come from the U.S. power grid<sup>9</sup>. An LCA model is developed following the ISO 14040 standards. It is assumed that organic waste needs to be disposed of and the environmental implications of the processes that generated the waste are therefore excluded. Utilizing MSW as feedstock implies a diversion of the waste, as

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<sup>9</sup> The process 'electricity, medium voltage, at grid from the ecoinvent database is used.

opposed to the cultivation of additional feedstock (e.g. biomass). The need to collect MSW regardless of its end-use implies no significant changes to the collection process and environmental burdens associated with collection are therefore excluded from the LCA. However, in order to process the waste and separate the organic fraction from the remaining waste stream, the waste feedstock needs to be pre-sorted and separated in a Materials Recovery Facility (MRF) (MSW classification)<sup>10</sup>. Further pre-treatment steps for comminution and drying are required (Fig.5).



**Fig.5** Process diagram of the MSW to polyolefin process (Source: own compilation). Mixed MSW enters the physical separation facility (MRF) in which the recyclable fractions are separated and a portion of the biodegradable fraction (BMSW) is sent to composting facilities (Waste Classification). The remaining fraction consisting of BMSW and a small percentage of plastics, inert materials and ferrous and non-ferrous metals is further pre-treated and then converted into syngas via gasification. Additional steps include gas cleaning and conditioning followed by FTS. The products of FTS consist of hydrocarbons of various chain length (syncrude) of which the naphtha fraction (C<sub>5</sub>-C<sub>8</sub>) is converted into polyolefins using syncrude upgrading, steam cracking and polymerization.

In this system, MSW is first separated to remove recyclables and shredded and milled to reduce size. It is then dried prior to gasification or moistened for anaerobic digestion, respectively. The syngas is then cleaned to remove tars, dust, alkali, BTX (benzene, toluene and xylenes) and halons. The cleaning stages envisaged are suitable for subsequent FTS. The six main stages of the life cycle considered

<sup>10</sup> (54) reported that there is some discussion as to whether MSW classification should be included in the analysis. Some authors share the opinion that this step does not need to be included in an LCA. They state the fact that MSW is anyways classified into the different waste fractions because it is economically feasible due to the value of recovered material and because of legal mandates for prior separation.

are: Classification (sorting), Pre-treatment (Fluff shredding/Drying), Gasification/FTS, FT Syncrude upgrading, Steam Cracking, and Polymerization. Technologies included represent existing processes that are available on pilot or demonstration scale (e.g. gasification system) as well as currently operated processes (i.e. naphtha steam cracker, etc.). The transport from the MSW classification plant to the conversion plant is taken as 50 km. The transport is performed by a 28t truck.

The analysis exclusively considers MSW destined for landfills and incineration plants. This excludes recyclables which are reused as well as agricultural and forestry residues. Commercial scale FTS plants utilizing organic waste as feedstock do not yet exist, but mass and energy balances on syngas generation from waste feedstock including raw MSW, BMSW and refuse derived fuel (RDF) (59,32,27,60,61) as well as data for subsequent FT syncrude production (62,63,32,64-66) are available from the literature. In fact, several studies indicate that in particular RDF would be a suitable feedstock for gasification-based FTS (32,61).

We assume that all BMSW destined for landfills and incinerators can be separated from the remaining waste either at the source or during the classification process (during which marketable aluminum, glass, steel and plastic material are recovered). The waste composition and energy content of the BMSW fluff diverted to the gasification plant is assumed to be similar to the U.S. average and is taken from (2,15,1). The wet tonnes of MSW constitute the mass that must be treated in the classification plant. The classification process is modeled based on (67) assuming that electricity is used for meeting all of the energy requirements in the classification process<sup>11</sup>. The analysis assumes average recycling and recovery rates as given in (15). Energy use is allocated as follows: BMSW fluff (37%), recyclables (i.e. glass, ferrous, non-ferrous, etc. 24%), compostable waste (9%), and scraps (30%). The input of BMSW fluff to the conversion plant is calculated based on the average energy content of the waste fluff after classification (11.588 MJ per kg wet BMSW fluff). The BMSW composition is: paper & paperboard (38%), wood (16%), food scraps (34%), and yard trimmings (13%).

Three technologies for converting BMSW fluff into synthetic gas ( $\text{CO} + \text{H}_2$ ) are selected and compiled from (68,32,69,64,27,60,61,56). Low-temperature wet gas cleaning is envisaged as cleaning process after gasification. Various reports are available describing the in-depth technical details of those technologies (see e.g. (70,27,71,72)) and therefore they are not explained in detail. Table 1 gives an overview of the conversion technologies selected.

**Table 1.** Technologies chosen for syngas production using gasification of RDF.

Data Source	(32,60,61)	(27,60)	(64)
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<sup>11</sup> The study by (67) looked specifically at classification processes that would be able to generate a clean RDF suitable for biochemical ethanol synthesis. We assume that this sort of classification system will produce a pure organic feedstock that would be suitable for subsequent conversion towards chemicals via gasification and AD.

Manufacturer	Batelle (BHTGS) <sup>1</sup>	MTCI ThermoChem <sup>2</sup>	Choren <sup>3</sup>
Type	Circulating fluidized bed gasifier (CFB)	Bubbling fluidized bed gasifier (BFB)	Two-stage entrained flow gasification (Carbo-V process)
Direct/Indirect heating	Indirect	Indirect	Indirect
Pressurized/Atmospheric	Atmospheric	Atmospheric	Pressurized
Air/Oxygen/Steam-blown	Steam/Air	Steam	Air
Temperature [°C]	766	843	400-600 (1 <sup>st</sup> step) 1300-1500 (2nd step)
Feedstock	RDF	RDF	RDF <sup>4</sup>
Water content (%)	20	20	20
Scale	Demonstration	Semi-commercial	Semi-commercial

<sup>1</sup>Batelle High Throughput Gasification System (BHTGS). <sup>2</sup>Manufacturing and Technology Conversion International, Inc (MTCI). <sup>3</sup>Only aggregated datasets for the generation of FT-liquids were available. <sup>4</sup>The study by (64) looks at woody biomass (willow-salix) for FT Diesel production. We assume that pre-plant classification produces an organic feedstock (RDF) that would be acceptable for gasification and subsequent FT liquids production using the Carbo-V process.

The Fischer-Tropsch synthesis (FTS) is based on modeling results from (64,66). Two different FT systems are investigated as part of this study. On the one hand, clean syngas generated by the BHTGS and MTCI gasification units is fed into a slurry-bed, iron-based catalyst FT-reactor system based on a model developed from public information and published in (66). The FT-model used in their study is based on data originally published by Bechtel/Amoco in 1993<sup>12</sup>. On the other hand, syngas generated from the Choren Carbo-V process is converted into FT syncrude using a cobalt catalyst in a tubular-fixed-bed reactor (TFBR). This process is based on aggregated inventory data (due to confidentiality issues) directly taken from (64,73). Although assumptions with regards to allocation and emissions profiles may vary somewhat from our LCA model, it was decided to use the aggregated dataset to cross-check results of the other two conversion systems investigated in this paper. Syngas characteristics and conditioning are critical for fuels and chemicals synthesis. High purity syngas (with low quantities of inert gas such as N<sub>2</sub>) is beneficial as it substantially reduces the size and cost of downstream equipment. Supporting process equipment (e.g. scrubbers, compressors, coolers, Water-Gas-Shift, etc.) can be applied to adjust the conditioning of the product gas. When using an iron catalyst the H<sub>2</sub>/CO ratio of the syngas should be adjusted to approximately 0.6<sup>13</sup>, while for cobalt catalysts a H<sub>2</sub>/CO ratio near 2.0 should be used (68). An autothermal reformer (ATR) using steam and enriched air/oxygen with partial CO<sub>2</sub> recycle is used for syngas preparation. It is important

<sup>12</sup> Baseline Design/Economics for Advanced Fischer-Tropsch Technology, DOE Contract No. DE-AC22-91PC90027, Topical Report Volume 1, Process Design – Illinois No. 6 Coal Case with Conventional Refining, October, 1994.

<sup>13</sup> The iron-based F-T catalyst promotes the water-gas shift reaction which produces hydrogen for the F-T synthesis reaction ( $\text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2$ ).

to point out, that varying calorific values of the product gas do not affect subsequent FTS as long as  $H_2/CO$  and impurity levels are met (68). No transportation is accounted for as it is assumed that the gasifier, syngas cleaning and FTS platforms are integrated and located within one conversion plant. The full amount of heat and the main part of electricity is used inside the conversion plant (note that excess electricity generated in the FTS platform is delivered to the gasifier to meet some or all of the energy requirements).

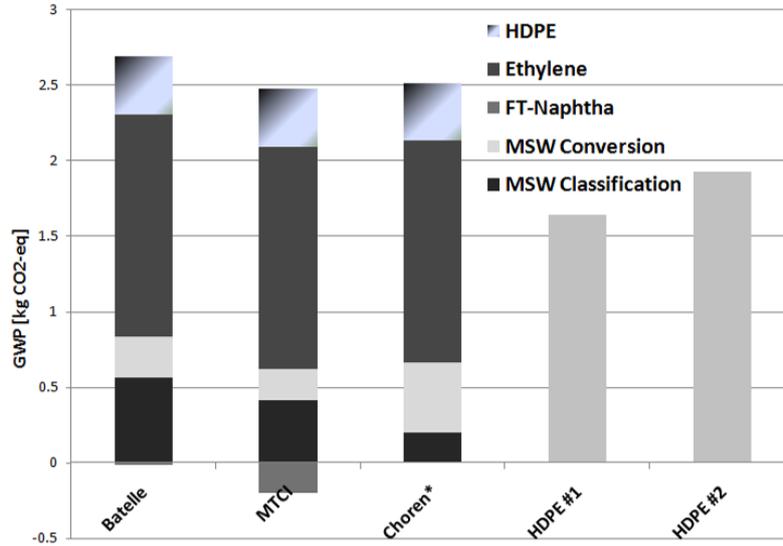
Fischer-Tropsch synthesis followed by upgrading of the FT raw liquid yields mainly naphtha and distillate as well as electricity. The FT product of primary interest to this study is naphtha that can be sent to a petroleum refinery. For this study, a *combined credit/allocation approach* is used for allocation. The environmental burdens from conversion and hydrocarbon recovery of the syngas-based FT plants are allocated based on the ratio of the energy content (Lower Heating Value) of the specific fuel relative to the total product. However, electricity co-produced is sold to the grid and can therefore be considered an end-use for FT-liquids and syngas. In order to compensate for this, excess electricity is treated with the credit approach, whereby electricity is assumed to come from the U.S. medium voltage grid.

(74) investigated the suitability of FT naphtha for use as a steam cracker feedstock and found that the substance mix was extremely well suited for the production of olefins (ethylene and propylene) by steam cracking. Accordingly, this study assumes the use of conventional naphtha steam cracking for the generation of ethylene. Data from the CPM database (75) and the ProBas database (76) is used to model the FT naphtha steam cracking process.

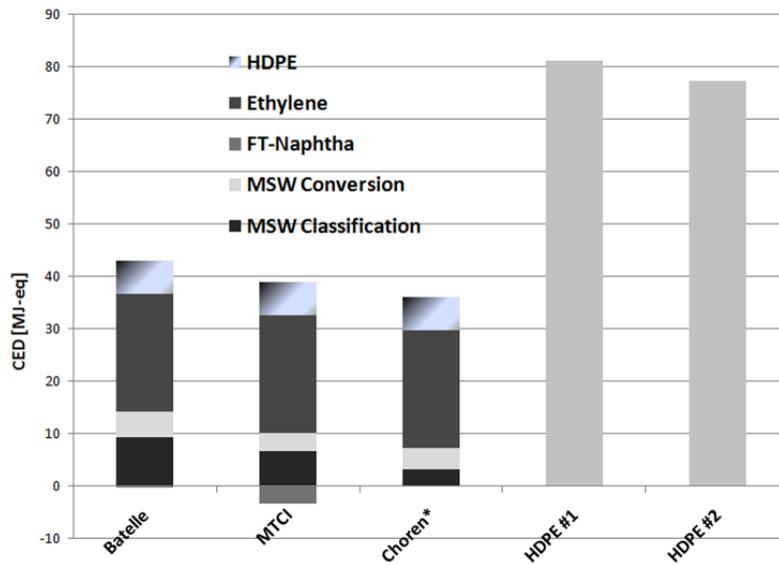
The life cycle inventory for high density polyethylene (HDPE) resin production from FT-derived ethylene is based on data from the U.S. life cycle inventory database (58,77).

#### 1.4.2.2 Results

The results (see Fig. 6 to 9) summarize the system-wide GWP (Fig. 6) and CED (Fig. 7) that we estimate would occur if BMSW from the MSW stream were used as feedstock for HDPE production. Fig. 8 considers the essential fact that the use of BMSW for chemical supply derives waste from landfills and thus may relieve the overall GHG balance. Results are shown for the *functional unit* of 1 kg HDPE at the factory gate and are compared to conventional (fossil-based) HDPE production routes. Data for these comes from the U.S. LCI database (HDPE #1) and ecoinvent (HDPE #2).



**Fig. 6** Comparison of the system-wide global warming potential (GWP) of producing 1 kg of HDPE from MSW with its fossil-based counterpart. Data for fossil-based HDPE comes from the US LCI database (HDPE #1) and ecoinvent (HDPE #2). \*The process ‘MSW Conversion’ for the Choren plant includes gasification and FT-naphtha production (aggregated dataset).



**Fig. 7** Comparison of cumulative energy demand (CED) of producing 1 kg of HDPE from MSW with its fossil-based counterpart. Data for fossil-based HDPE comes from the US LCI database (HDPE #1) and ecoinvent (HDPE #2). \*The process ‘MSW Conversion’ for the Choren plant includes gasification and FT-naphtha production (aggregated dataset).

The comparison shows that GWP associated with the waste-derived polymers is with 2.7 to 2.3 kg CO<sub>2</sub>-eq slightly higher than their fossil-based counterparts. A large share of total GWP is due to steam cracking, during which FT-naphtha is converted into ethylene feedstock, as well as MSW classification where the raw MSW is separated into BMSW fluff and other waste fractions. MSW conversion (gasification) leads to roughly 0.21–0.27 kg CO<sub>2</sub>-eq for the Batelle and MTCI systems investigated. Aggregated data for the Choren plant indicates a GWP of 0.463 kg CO<sub>2</sub>-eq associated with the conversion step from BMSW to FT-naphtha. During the FTS step, electricity is co-generated, most of which is used internally. However, the MTCI conversion system generates a small amount of excess electricity (0.23 kWh/kg FT liquids) which is assumed to offset conventional electricity from the U.S. national grid (therefore the negative GWP for FT-naphtha generation). The figure shows that the Batelle conversion-plant leads to the highest GWP, followed by the Choren and MTCI design. The reason for this is that, according to the data gathered, the Batelle conversion-plant requires slightly higher inputs of BMSW fluff (by energy content) and electricity to generate a clean syngas for use in the FTS platform. As a result, transportation and energy required for MSW classification contribute more towards GWP and excess electricity exported to the grid is minimal.

In contrast, results for CED are highest for fossil-based HDPE (77.3–81.0 MJ-eq). This is followed by 42.61 MJ-eq for the Batelle conversion facility and 35.97 and 35.57 MJ-eq for the Choren and MTCI systems, respectively. CED of the MSW-based routes is about half that of the conventional fossil-based routes. The CED indicator encompasses non-renewable (i.e. fossil and nuclear) as well as renewable (i.e. biomass, wind, solar, etc.) energy demand. However, renewables account for less than 1% of total CED. The reason that CED for the waste-derived polymers is lower than for their fossil-based counterparts is the fact that the intrinsic energy content of the waste feedstock is not accounted for (cut-off approach). In contrast, for fossil-based polymers the direct and indirect energy consumption of e.g. natural gas and crude oil resources used to synthesize the HDPE polymer (some of which is later present as ‘feedstock energy’ in the final product) are accounted for in the CED values. Similar to GWP, steam cracking and MSW classification, both being very energy intensive processes, account for a large share of CED. The magnitude to which MSW conversion and FTS contribute to total CED depends on the amounts of waste feedstock transported to the gasifier and further energy and materials requirements for the conversion facility. Both CED and GWP for the MSW classification step of the Choren plant are small compared to the Batelle and MTCI conversion systems. This is due to the fact that in the Choren design, which is optimized for FT diesel production, less naphtha is produced and therefore the largest part of CED and GWP associated with BMSW provision to the conversion system is allocated to the FT-distillate (for diesel).

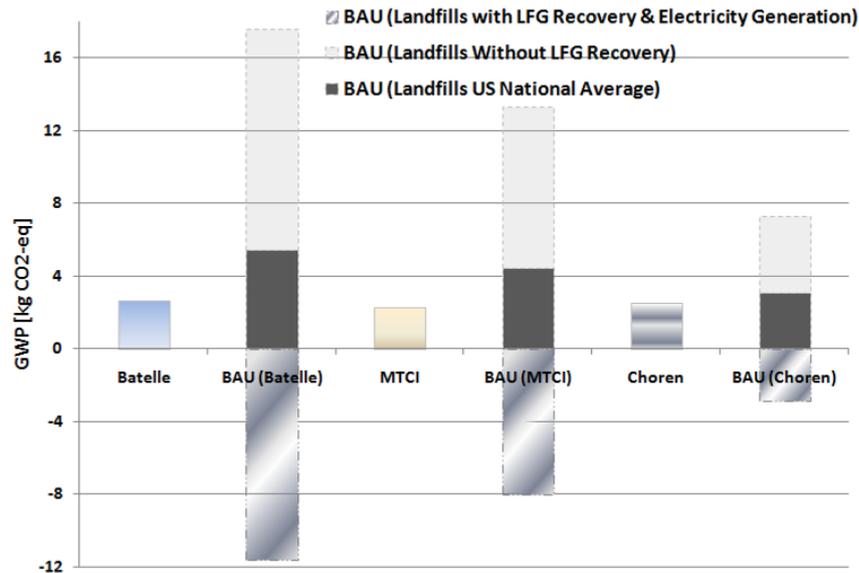
### 1.4.2.3 System Expansion – Avoided Landfilling

When paper, wood, food scraps and yard trimmings are landfilled, anaerobic bacteria degrade the materials, producing methane and carbon dioxide. Although landfills during use operate as net-carbon sink (and as a source afterwards), methane generated is counted as an anthropogenic GHG because degradation would not take place if the BMSW were not landfilled. The impact of waste diversion from landfills is significant for landfills with no recovery equipment (i.e. landfill gas (LFG) recovery for flaring or electricity generation). In contrast to many countries in Europe, in the United States and many developing countries significant amounts of BMSW are sent to landfills. We use system expansion to compare: 1.) GHG emissions associated with the production of 1 kg HDPE from BMSW (*'carbon recycling'*) with 2.) GHG emissions associated with landfilling the BMSW and the production of 1 kg of fossil-based HDPE (*'business-as-usual (BAU)'*). We use emission factors from the WARM model for the United States to estimate the GHG emissions from landfilling the BMSW fluff (78).

Given the U.S. national landfills average from the WARM model, the emissions avoided of removing 1 kg of wet BMSW (with the average waste composition mentioned above) from landfills equals 0.167 kg CO<sub>2</sub>-eq. As a result, the 'BAU – U.S. National Average' case would lead to a higher system-wide GWP of 5.5 to 3.1 kg CO<sub>2</sub>-eq per kg of HDPE produced when compared to the production of 1 kg of waste-derived HDPE (carbon recycling). With 3.1 kg CO<sub>2</sub>-eq, GHG emissions are lowest for the BAU case in which BMSW, otherwise used as feedstock in the Choren plant, is landfilled and HDPE is produced from fossil-fuels. This is due to the fact that most of the BMSW is used to produce distillate (for fuels) and less for naphtha (for HDPE), and thus a major part of landfill emissions in the BAU scenario are allocated to the distillate. The results indicate that, accounting for average landfills emissions in the U.S., carbon recycling may have the potential to lead to an overall reduction in GWP when compared to current (BAU) waste management and HDPE production practices (Fig. 8).

However, the magnitude to which landfill diversion results in net GWP reduction depends significantly on whether landfill gas (LFG) recovery and energy recovery equipment is deployed and how effectively it is operated. Flares and generators on-site have the potential to convert methane into CO<sub>2</sub>, therefore reducing GWP. If only landfill systems without LFG recovery equipment are considered, system-wide emissions of the BAU case would amount to 12.1 to 4.2 kg CO<sub>2</sub>-eq per kg HDPE (BAU Landfills without LFG Recovery), while only considering landfills with LFG recovery equipment and electricity generation would amount to -11.6 to -2.9 kg CO<sub>2</sub>-eq in GHG savings (BAU Landfills with LFG Recovery & Electricity Generation), therefore competing with polymer production about the most beneficial use of BMSW to reduce GHG emissions (Fig. 8). The difference between landfills without LFG recovery equipment and those with LFG recovery

equipment illustrates the impact that assumptions on waste diversion can have on the net GWP of the expanded system.



**Fig. 8** System expansion accounting for the fact that in a business-as-usual (BAU) case HDPE is produced from petroleum and BMSW is landfilled. The amount of BMSW going to landfills depends on the feedstock requirements of the carbon-recycling systems (Batelle, MTCI and Choren). U.S. landfill net emission factors from the WARM model are used. Data for fossil-based HDPE comes from the US LCI database (HDPE #1) and ecoinvent (HDPE #2).

### 1.4.2.3 Discussion

Ignoring the fact that waste needs a safe final disposal, the use of BMSW for the production of polyethylene seems to result in only slightly higher GHG emissions as compared to conventional fossil-based routes. Under the same assumption, CED of the MSW-based polymer production routes was found to be roughly half that of conventional HDPE production. The impact of BMSW landfilling presents the greatest system uncertainty. Depending on the landfill system chosen, these assumptions can change GHG emissions for the BAU scenarios from positive to negative. When using U.S. national landfills average data, carbon recycling systems investigated in this paper may have the potential to significantly reduce GHG emissions. However, the required capital for methane recovery installations particularly in developing countries may be lacking, and the low price of commercially produced gas may not make methane recovery an economically viable option. In addition, landfill space may be limited, in particular in urban areas. These con-

ditions could make carbon recycling technologies an attractive option for developing countries and emerging economies in the future. Furthermore, the WARM model makes key assumptions that are critical for the interpretation of our results. For instance, when LFG is recovered for energy production, co-product credits for the displacement of an equivalent amount of energy from the U.S. electricity grid, which is dominated by coal with high GHG emissions, are applied by the model. Therefore, considering a less carbon-intensive electricity mix (e.g. in a future scenario with larger shares of electricity being supplied by renewable energy systems) could change the balance more in favor of carbon recycling systems. Further investigations should also consider other end-of-life waste management techniques such as combustion and composting and include an uncertainty and sensitivity analysis (using e.g. economic allocation). Furthermore, the analysis should be expanded to other impact categories, including total material requirement (TMR), acidification, eutrophication and health impacts, as well as cost. Finally, we assumed that MSW classification is required to obtain a clean gasification feedstock. MSW classification leads to roughly one fifth of these impacts and therefore excluding this process step from the LCA would result in further lowering of life-cycle wide impacts. This may be justified in circumstances where classification takes place solely due to the value of recovered material (e.g. plastics, metals, etc) or because of legal mandates prior to separation.

## 1.5 Conclusion

Carbon recycling, in which organic waste is recycled into chemical feedstock for material and fuel production, may have the potential to provide benefits in resource efficiency and a more cyclical economy – but may also create ‘trade-offs’ in increased impacts elsewhere. Preliminary LCA model results derived from the combination of various existing technologies (i.e. MSW classification, gasification, FTS, steam cracking, etc.) and considering landfill diversion, indicate that the use of biodegradable waste for HDPE production could lead to a reduction in system-wide GHG emissions when compared to conventional fossil-based production routes. However, as yet the conversion technologies assessed do not work in the integrated fashion modelled in this paper.

Developing pilot plants for the conversion of BMSW into base chemicals such as HDPE could be a future option in particular for mega-cities in developing countries and emerging economies with high-volume generation rate of organic waste and a lack of landfill gas recovery equipment and landfill space. Varying the process parameters of technologies such as FTS could allow the generation of both base chemicals (such as naphtha for polymers) and liquid fuels. The potential of gasification technologies to destroy harmful microorganisms at high temperatures

and concentrate hazardous metals in the slag and ash could become of increasing interest for developing countries in the future.

In summary, the described technologies of carbon recycling may contribute to further develop the waste management sector towards a more sustainable resource management. Besides the recycling of carbon flows, also the extraction, use, recycling and disposal of all material resources should be considered when developing the physical basis of society and economy towards increased sustainable resource management.

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