

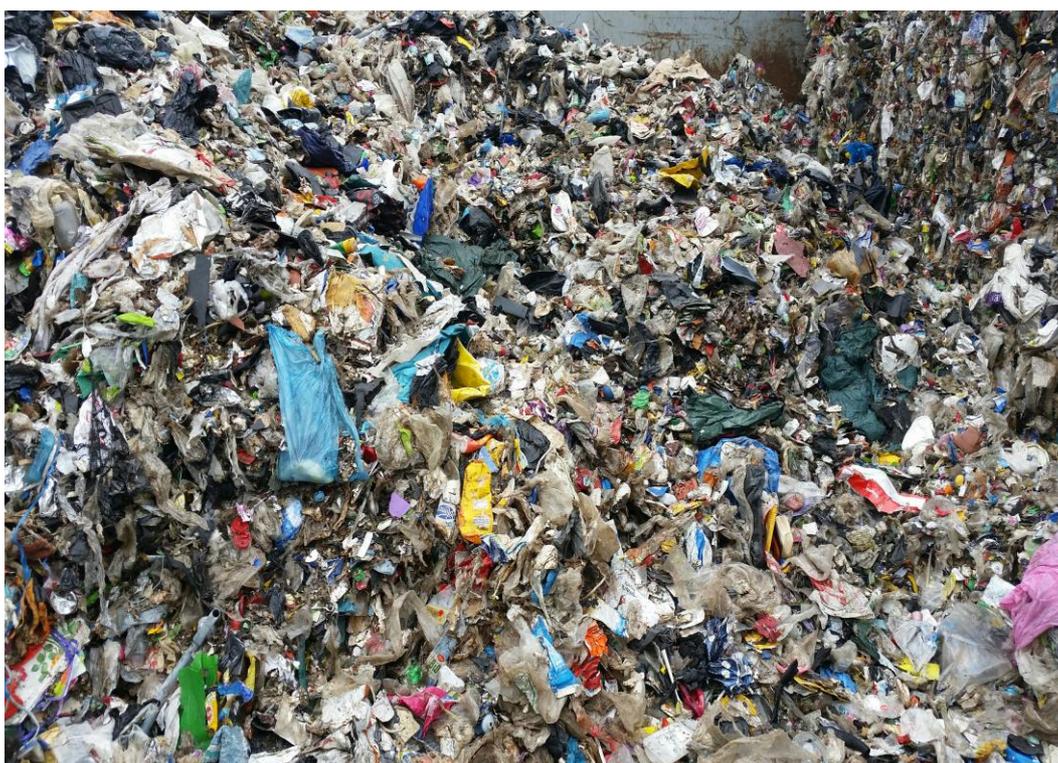


**IEA Bioenergy**  
*Technology Collaboration Programme*

# Trends and drivers in alternative thermal conversion of waste

IEA Bioenergy: Task 36

September 2020





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# Trends and drivers in alternative thermal conversion of waste

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**Acknowledgement:** Funding of the BKV-study on Thermal processes for feedstock recycling of plastics waste by BKV GmbH and Plastics Europe AISBL is gratefully acknowledged.

IEA Bioenergy: Task 36

September 2020

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**Published by IEA Bioenergy**

## Abstract

IEA bioenergy Task 36 “Material and energy valorisation of waste in a circular economy” prepared this report about trends in waste management for the example of municipal solid waste (MSW). Within the waste hierarchy, recycling is given preference over recovery, and waste-to-energy (WtE) conversion is given preference over landfilling. MSW is non-hazardous household and commercial waste, of which more than one third typically is biogenic in origin. Incineration represents the state-of-the-art WtE technology; alternative thermal treatment technologies such as gasification and pyrolysis have had far fewer applications to MSW due to economic factors and relatively low technology readiness. This is a situation that is currently changing. Specifically in the European Union (EU) technologies develop and new pathways are sought.

Major trends in the EU are driven by legislation and implementation goals, some of which are country specific:

- banning of landfilling in combination with limited social acceptance and, in some countries, legal restrictions for additional incineration capacity
- increasing waste generated or imported in combination with limited incineration capacities have led to increased waste treatment cost (gate fees) and waste exports
- recycling rates that are lower than EU and national Circular Economy objectives
- global demand for sustainable routes for waste processing, particularly with regards to reducing greenhouse gas (GHG) emissions, and
- heightened social awareness and concerns about environmental impacts including climate change and marine littering.

Key opportunities driven by these trends are related to the adoption of non-incineration thermal technologies

- for energy recovery as a response to decreasing public acceptance for direct waste incineration, and
- as a pathway to chemical recycling of waste, which accelerates the transition to a Circular Economy. This involves co-processing of biomass and waste to improve the economies of scale associated with biomass conversion plants.

The upcoming report discusses both trends impacting solid waste management systems within EU countries as well as selected alternative thermal treatment technologies. Aspects concerning technology readiness and affordability are highlighted in this report as well as the need to combine mechanical waste pretreatment and sorting with thermochemical treatment in order to increase recycling rates and to improve economics.

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# 1 Introduction

One of the keys for a sustainable development of human society is the efficient use of resources. This is a particularly challenging task especially as resources and energy are inextricably linked in the Circular Economy (CE). Implementation of a Circular Economy aims to minimize the impact of the economy on the environment and the climate, more specifically to minimize greenhouse gas emissions, energy demand, pollutants release, and/or distribution of scarce resources. Simultaneously, this needs to be accomplished at affordable cost to ensure business viability and to contribute to social acceptance of CE policies. Successful implementation of a Circular Economy needs to be both resource and energy efficient in order to fulfil the multi criteria optimization objective.

Scarcity of resources and the need to drastically reduce environmental impacts are key drivers of waste management systems. In a Circular Economy, these aspects are addressed in a managed and complementary fashion. Moving towards a Circular Economy means that we may need to adapt existing and developing waste management systems, in particular as we strive towards achieving this vision of a future carbon neutral society relying on (i) renewable energy sources, (ii) carbon recycling technologies, and (iii) integrated process chains combining both.

It is also difficult to remove the need for carbon entirely in many industrial processes. In a future independent of the use of fossil hydrocarbons, carbon will be available from biomass, anthropogenic wastes and residue streams, and from unavoidable CO<sub>2</sub>-streams. Thus, the feedstocks utilized by the chemical and transportation fuels industries will change dramatically. Continuously increasing manufacturing of chemical products as well as high energy density compounds (e.g. aviation fuels) will require these carbon feedstocks, and in order to meet the climate protection targets, additional short-term measures need to be implemented specifically in the transportation sector.

Clearly, waste recycling must be a pillar of the carbon cycle concept. Recycling processes are either physical (meaning that materials are separated from each other but the molecular structure is not changed) or chemical (meaning that the molecular structures are changed in new materials are made from waste). Waste recycling requires the rigorous implementation of waste collection in general, but can be an effective means of recovering materials that can be re-used and recycled using standard, well-established processes. Not all materials can be recycled, however, and in the absence of energy recovery, these are inevitably sent to landfill.

Waste-to-Energy (WtE, defined for the purposes of this report as state of the art waste incineration with extensive flue gas cleaning, heat recovery, and bottom ash treatment) is an important aspect of sustainable waste management, whereby energy (heat and power) can be extracted from landfill-bound waste streams. WtE is preferable above waste disposal (landfilling), however it does not maximize material recycling up to the thermodynamic constraints and it does not avoid CO<sub>2</sub>-emissions of the waste feedstock, itself.

Alternative thermal conversion of waste (also referred to as “advanced technologies” or “alternative thermal treatment”) considers alternative processes to incineration that do not fully oxidize the waste feedstock. This allows for products other than heat and power, and thus offers the potential for such technologies to be part of systems that support significantly higher material recycling rates. To be technically and economically viable these thermochemical conversion technologies have to be integrated into waste processing chains. Thus, advantages in waste feedstock flexibility, resource efficiency, and energy efficiency are key to the application of alternative thermal treatment of waste.

This report outlines recent and current trends that drive the development and deployment of alternative thermal conversion of waste. After a brief introduction to waste feedstocks, it focusses on waste management frameworks in the EU and it provides examples of country specific conditions in order to provide context to the opportunities and barriers in application of these technologies (section 2). Processes to convert waste into feedstocks for alternative thermal treatment processes are discussed in subsection 2.3. Then, key alternative thermochemical conversion technologies are reported briefly and systematically, and applicability and risk (technology readiness) as well as economic aspects are discussed on the bases of

two example cases (section 3).

This report does not address comprehensive evaluation of alternative thermal conversion of waste technologies versus state-of-the-art incineration and in combination with waste prevention, replacement of established materials, waste collection and sorting systems, etc. That is to be evaluated by the life cycle assessment method of alternatives in order to prepare decisions about waste management systems design and modification.

## 2 Waste Policies and Regulations

The scope of this report is treatment of municipal solid waste (MSW), which involves post-consumer as well as commercial waste. Other important waste fractions with high biogenic content are agricultural production residues, forestry residues, or some fractions of construction demolition waste. These fractions are not considered here. World-wide MSW volume has exceeded 1.3 billion tons per year and increases steadily.

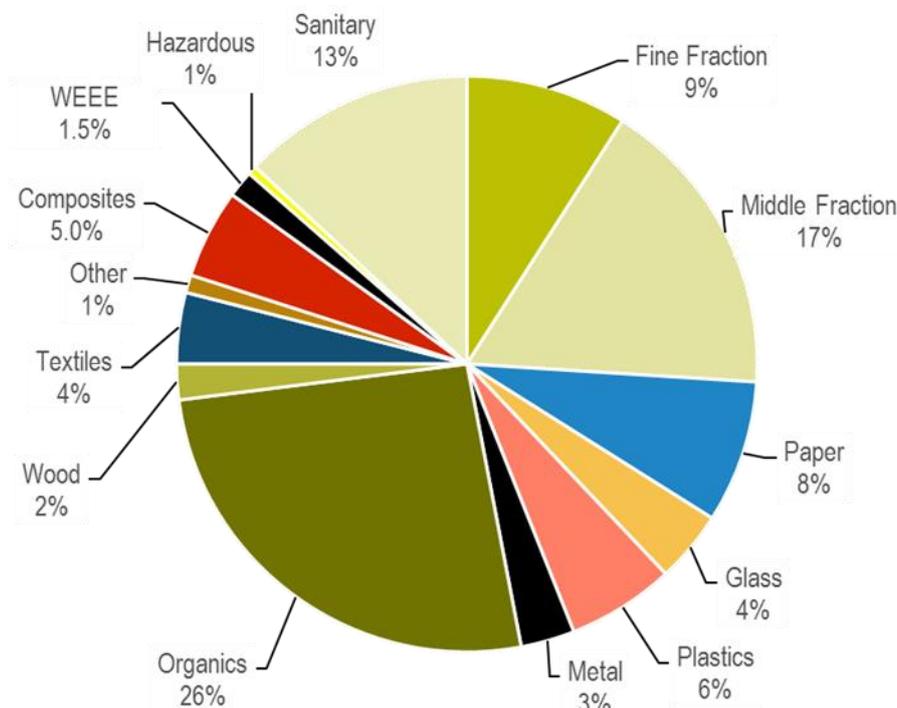


Figure 1: Typical composition of residual household waste in developed countries [according to BKV-study, 2019], where WEEE stands for waste electrical and electronic equipment

Typically, the organic content of MSW is approximately 50 to 60 weight%. The composition of MSW varies geographically and seasonally. Seasonal effects specifically impact the moisture content of MSW and thus the heating value. The per capita amount of waste produced as well as aspects of the composition of this waste, is related to economic maturity indicators such as the gross national product. In general, the amount of waste produced correlates with economic growth rates and it is the highest in developed countries.

Figure 1 shows the heterogeneity of the residual household waste fraction of MSW. Typically, in developed countries MSW contains approximately 45% (inert) mineral material as well as up to 45% post-consumer end-of-life (EoL) goods. These EoL goods represent the metals, the plastics and the glass fractions. These fractions along with paper represent the major targets of recycling efforts.

Waste management systems are country specific and vary widely. Treatment of waste produced generally includes collection and often sorting, re-use (recycling) of specific sorted fractions if possible, and either incineration or landfilling of the residual waste. Incineration is an established Waste to Energy (WtE) pathway which reduces the amount of waste for disposal to just the mineral fraction due to combustion of

the organic content and allows the utilization of the combustion heat for heating and for generation of electricity. During incineration, the waste carbon content is converted to CO<sub>2</sub>. During landfilling, the waste carbon content is converted to CO<sub>2</sub> and methane. Whether waste incineration is preferred over landfilling or is applied widely depends on many factors including social acceptance. This is typically subject to the country specific waste regulatory framework. WtE contributes to sustainability goals by avoiding greenhouse gas emissions from fossil sources and by minimizing the environmental impact of waste if state-of-the-art flue gas treatment is applied properly. In addition, it prevents the generation of methane in landfills which is a far more potent greenhouse gas compared to CO<sub>2</sub>.

## 2.1 EU DIRECTIVE FRAMEWORK

In many regions and countries worldwide, and specifically in the European Union, the waste hierarchy (Figure 2) is the guiding principle of waste management.

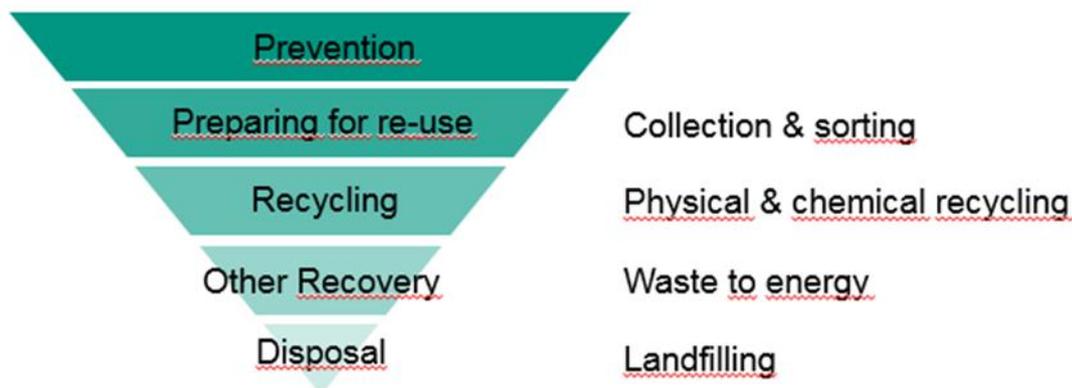


Figure 2: EU waste hierarchy applied to municipal solid waste (MSW) and plastics waste

The updated European Union regulatory framework forms the basis for national legislation and sets the CE targets to be incorporated into the climate objectives. Herein, the 2008 Waste Framework Directive [2008/98/EC] where recovery operations and recycling were made guiding principles sets the target for recycling of municipal solid waste to 60 wt-% by 2030.

Against the backdrop of an increasing production of packaging waste, an increased emphasis on the problem of microplastics in the marine environment, and the need for action in dealing with residual waste locally as a result of Chinese and other Asian import bans on waste, the EU Commission published the first EU plastics strategy in January 2018 [COM(2018)]. In this strategy, 55% of plastic waste will have to be recycled in 2030 which will require the deployment of additional recycling capacity of ca. 10 million t/a. The individual measures to be taken by the EU-28 countries are currently focussing on packaging waste [Witts et al., 2018]. A particular challenge is that the actual recycling rate of plastics will need to increase significantly to meet these targets. As a minimum prerequisite, suitable waste collection as well as sorting systems have to be implemented, and depending on the impact of these, additional technology pathways may be needed.

There are numerous barriers to the physical (mechanical) recycling of plastic waste resulting in waste recycling rates that are below the targets mentioned above. These include: composite materials that cannot be separated mechanically, challenges associated with sensor based sorting technologies such as black plastics, end-of-life products in complex mixtures and the associated high costs of separation, and ensuring the quality of secondary raw materials to maximize recycling. The recycling rate is higher for production waste than for post-consumer waste due to the often single-origin and low contamination. To date, post-consumer plastics waste consists in equal shares of packaging materials and of engineering plastics. The size of the gap between current recycling rates and the targets varies from country to country, such as waste collection systems and application of (physical) sorting as a prerequisite for recycling do.

The aforementioned challenges have increased interest in the potential of chemical recycling (also referred to as ‘feedstock recycling’ and ‘waste-to-chemicals’) to contribute to the recycling rate as an extension to waste sorting and as an alternative to waste incineration. Moreover, by reducing the fossil feedstock share in chemical manufacturing, chemical recycling of waste providing suitable chemical feedstock can reduce the carbon footprint of the manufacturing industry. The technology pathways for such approaches are discussed in Section 3; the following subsection details the waste management situation for three European countries.

## 2.2 EXAMPLES OF COUNTRY SPECIFIC SITUATIONS AND REGULATIONS

Figure 3 illustrates the diversity of waste management systems in the EU-28 countries and its neighbours. Note that the numbers show the shares of waste treatment on an input basis (mass), as opposed to an output basis (which would translate into actual recycling rates). Many countries still employ landfilling to a large extent; this contributes significantly to the recycling rate shortfalls and more broadly the adoption of circular economy principles.

While the application of state-of-the-art waste incineration is increasing globally, this is strongly impacted by national regulation and perception, and we can see that incineration is used in some countries only. For example in France, legislation limits the application of incineration to a maximum of one third of waste produced. Meanwhile, in the UK, the investment in incineration and alternative thermal treatment of waste is rising due to the partial landfill banning in combination with incentives for alternative technology implementation. In general, implementation of landfilling bans corresponds with increasing landfilling cost and thus supports recycling as well as WtE. Figure 4 shows the landfilling policy in several EU-28 countries.

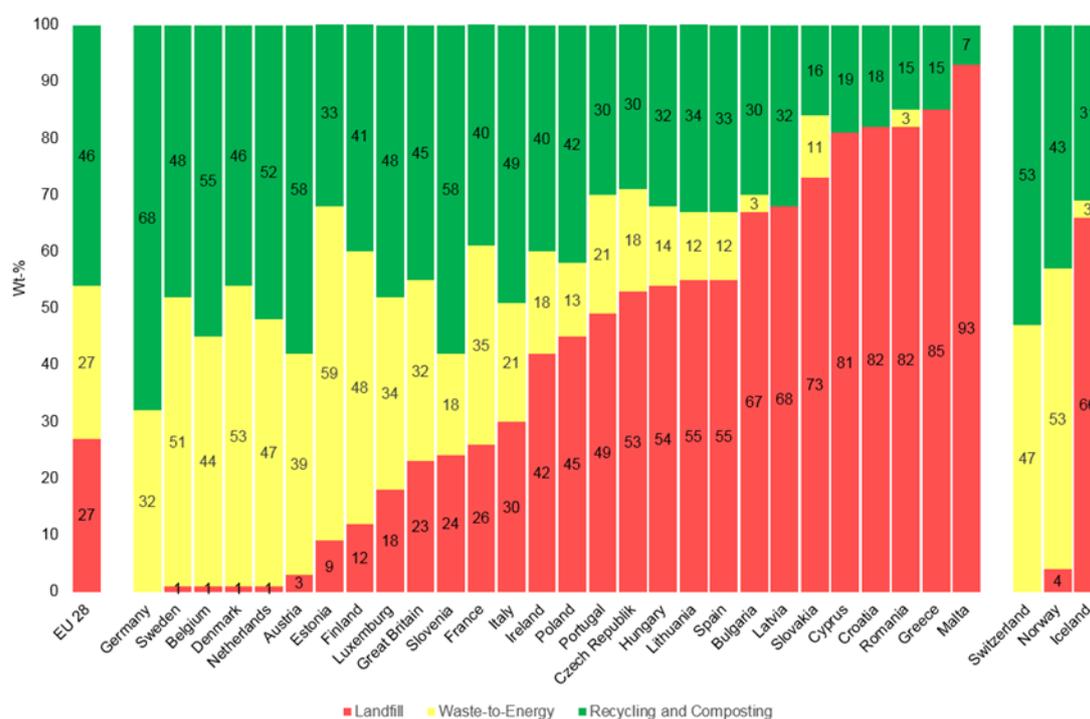


Figure 3: European waste treatment status in 2014 [according to Spohn, 2018]

### Germany

With a population of ca. 81 million in Germany, MSW currently totals more than 50 Mt/a. German collected residual household waste amounts to ca. 20 Mt/a. In addition, separately collected plastic waste totaled ca. 5.9 Mt/a [CONSULTIC, 2016]. This plastic waste is predominantly packaging waste (post-consumer) while the majority of plastics produced ends up in longer-life products especially of the building construction and the automotive sectors. Of this collected plastic waste was 2.7 Mt recovered mechanically e.g. in automated

sensor-based sorting plants followed by post-processing and less than 0.1 Mt was recycled chemically; about 53 wt-% (3.1 Mt) of plastics were converted thermally by waste incineration. This non-thermal recycling rate is stagnant in Germany while the amount of MSW continues to increase.

In 2005, Germany implemented a landfill ban on MSW. At present, waste incineration and co-incineration capacities of 29.7 Mt/a (including 20 Mt/a MSW incineration, dedicated refuse derived fuel RDF, cement, and coal power plants) are fully utilized and MSW incineration gate-fees significantly exceed €100/t. Several waste collection systems are in place (being the task of the municipalities) for different kinds of waste, contributing to the recycling of metals, paper, glass, and packaging plastics. Mechanical pretreatment (see Chapter 2.3) is applied to roughly 25% of the residual household waste, whilst mechanical-biological treatment (MBT) of MSW is of less importance. Installed capacities do not increase for any of the treatment processes, currently. Treatment and sorting residues either are incinerated or have been exported. When co-processing RDF, the operating permit of any plant depends on the regulations for waste treatment plants. This applies e.g. for cement processing or waste wood combustion plants.

Due to China's waste import ban, in combination with increasing perception about waste exporting, the gap between treatment capacities and sorting residues produced has increased.

Under the EU Waste Framework Directive [2008/98/EC] and the EU Circular Economy directive [2018/852/EU], the new German Packaging Law [VerpackG, 2017] came into effect in January 2019. It established more ambitious material recycling targets including a 63.5 wt% target for packaging plastics in 2022. Furthermore, within this packaging waste focus, high material recycling ("Plastics-to-plastics") shares are required [Fischer, 2019].

The majority of plastics recovered by separate collection and sorting technologies are used as recyclates (recovered polymers) in the aforementioned plastic production. Plastic products of highly regulated quality requirements such as food packaging or engineering lightweight materials have a low recycling rate, often because existing sorting technologies cannot achieve the stringent specifications.

Being in the focus of society and policy makers, plastics markets undergo a change, as shown by a 60% recycling self-commitment of the European plastics producers (see [www.plasticseurope.org](http://www.plasticseurope.org)). However, because recycling rates have been flat, this has been a challenge, as recycled plastic feedstocks of sufficient quality are not available. This paves the way for different kinds of recycling technologies. Specifically, chemical recycling opportunities are in the focus of plastics producers as well as waste processing industry searching new outlets for all different kinds of mixed waste sorting residues.

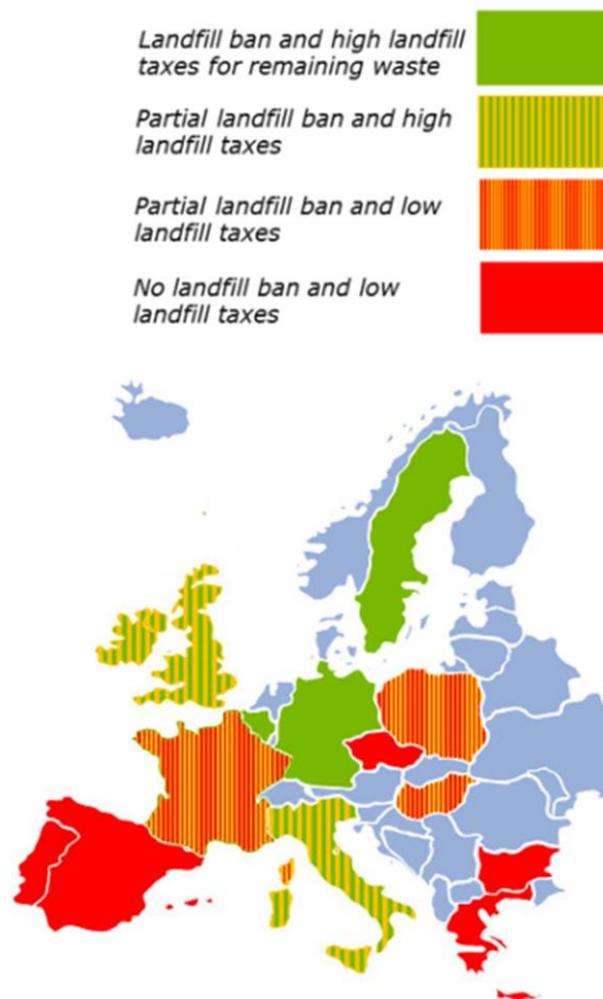


Figure 4: Map of the weight of policy related to waste landfill in the examined European countries [De Beer et al., 2017]

## Italy

With a population of ca. 60 million, about 29.6 Mt of MSW were produced in Italy in 2017, the major constituents being organic residues (35.7% in weight), paper and cardboard (22.6%), plastic and plastic packaging (2.8%) and glass (7.6%) [ISPRA, 2018]. The separate collection of the MSW reached the 55.5%, although still remaining below the national target [Legislative Decree n. 152/2006] set for 2011 (69%) and 2012 (65%) and with a significant difference at local scale [ISPRA, 2018].

Of the total amount of MSW separately collected (about 16.4 Mt in 2017 [ISPRA, 2018]), the organic fraction was the main component (40.3%) followed by paper (19.9%) and glass (12.2%) fractions, while plastic residues account for around a 7.8%. 23% (6.9 Mt) of the produced MSW was landfilled directly and 18% (5.6 Mt) sent to energy recovery [ISPRA, 2018]. About 20% (5.9 Mt) of the organic fraction from the separated collected MSW was biological treated: 39.9% in 31 integrated aerobic/anaerobic facilities (a type of waste management that recently showed a significant growth in Italy), 4.9% in anaerobic digestion plants, while the main part (55.2%) was sent to composting facilities [ISPRA, 2018].

Around 35% of the MSW (about 9.5 Mt) was sent to in MBT plants (130 facilities in operation in 2017) before landfilling or energy recovery. The output of this treatment represents 46% of the total MSW sent to incineration/co-incineration (as solid recovered fuel SRF, dry fraction or bio-dried fraction) and 93% of the total landfilled MSW (as bio-stabilized waste) [ISPRA, 2018].

For MSW and assimilated waste, a reuse and the recycling target of 50% by 2020, as material sent to recycling, was introduced in Europe by the [Directive 2008/98/EC] (implemented in Italy by the Legislative

Decree 205/2010). According to [ISPRA, 2018], in 2017 an average of 49.9% of waste recycling was achieved in Italy. The main fractions (by weight) sent to recycling include the organic fraction (41.3%), paper and cardboard (26%), glass (16.2%), followed by wood (6%), plastics (5%) and metals (2.5%) and, with a lower share, the WEEE (1.7%) and the textile (1%) fractions.

Regarding packaging management, a system of supply chain consortia was promoted and introduced. The packaging waste collected separately (both domestic as well as commercial & industrial C&I) must be sent to CONAI (the National Packaging Consortium), that is organized in specialized consortia for steel (RICREA), aluminum (CIAL), paper and cardboard (COMIECO), wood (RILEGNO), glass (COREVE) and plastics (COREPLA). Other private consortia are operating for WEEE, EoL tires and rubber, EoL vehicles, textiles, etc.

According to [ISPRA, 2018] in 2017 an overall recovery of packaging waste of 78% was achieved, with a (material) recycling rate of about 67.5 % and an energy recovery rate of about 10.5% (in the national incineration and co-incineration plants). Landfilling accounted for 22% (2.9 Mt). In detail, the amount waste sent to recycling was 75.3% for steel, 63.4% for aluminium, 79.8% for paper/cardboard, 60.1% for wood, 72.8% for glass and 43.5% for plastic packaging.

The European directive [2018/852/EU] on circular economy, not yet implemented by the Italian regulation, raised the target for material sent to recycling from packaging and packaging waste previously set by the Directive 94/62/EU. This new target by the 2025 was already achieved in Italy with the exception of plastics. Recycling of plastic waste involves around 300 facilities [UNICIRCULAR, 2019]. The latest available data shows an amount of plastic packaging entering the market of about 2.3 Mt in 2018 with an overall recovery (material recycling + energy recovery) of about 2.0 Mt, (87% of the total) and a material recycling share of about 45%. The residual part (13%) was landfilled. The production of secondary plastic materials (MPS) increased from 10% in 2014 to about 13% in 2017, with an average yield of the waste processing (80%) not significantly changing. The rejects of the recycling process are mostly reused to produce MPS or for other material recovery. Only an amount less than 10% is sent to incineration/co-incineration plants or is landfilled.

Italy is among the few European countries that started the recovery/recycling of all types of plastic packaging, and not only those of higher market value (e.g. PET and HDPE bottles). Problems occur in the recycling of some plastic waste streams in terms of availability and costs and the sector was affected by the China ban, especially with respect to the management of plastic films (LDPE). Short-term Italian forecasts (2020) are oriented towards an increase in the consumption of plastic packaging (2.3 Mt), in the amount sent to recycling (47%) and to energy recovery (47.1%) [UNICIRCULAR, 2019].

## Sweden

According to the Swedish Waste Management Association [Avfall Sverige, 2018], with a population of ca. 10 million Sweden generated ca. 4.8 Mt of MSW during 2017 representing a 2.5% increase over the previous year. Almost one third of this (ca. 1.6 Mt) was sent for material recycling, which includes metals, plastics, paper, cardboard and glass waste fractions. Half of the amount produced (ca. 2.4 Mt) was used in energy recovery in order to fulfil the Swedish energy and heat demand.

From an energy perspective, 18.3 TWh of energy was produced from MSW, which is the highest energy produced per ton of waste in EU (ca. 3 MWh/t). Biological recycling accounted for 15.5% of the total MSW, which represents a 2.1% decrease over the previous year. The amount of MSW landfilled in Sweden decreases every year, and only 0.5 % of it was landfilled during 2017, which is a result of the restrict legislation on landfilling implemented by the Swedish government and which started with a ban on landfilling combustible waste in 2002 and organic waste in 2005.

The Circular Economy directive [2018/852/EU] sets higher targets for material recycling among the EU members in order to promote the concept of a CE. More specifically, it is expected that at least 55% of MSW in the EU will be recycled to new material by 2025, followed by an increase to 60 % by 2030 and to 65% by 2035. In addition, 65% of all packaging should be recycled material by 2025 and reach 70% by 2030. The

[Swedish Protection Agency, 2018] conducted follow-up studies on producer responsibility in Sweden. The studies showed that 69% of this packaging was sent to material recycling in the country in 2016 which means that the target set by the EU directive was already met by then. Sweden continues with its goal of increasing material recycling rates and therefore has set more strict targets than the EU.

The main principle behind the Swedish waste management is that those complex materials for which there are no recycling technologies available and that are combustible are sent to energy recovery mainly by incineration. Incineration remains as the preferred option for hazardous waste. The recycling rates of glass, metal and paper are high compared to plastics [Avfall Sverige, 2018]. Recently, recycling companies made technological improvements, mainly on the automated sorting, that allows other fractions to be recycled more efficiently such as plastics and textiles [SYS AV, 2019]. Therefore, cleaner fractions are being produced at the recycling facilities. Some fractions such as LDPE, HDPE and PET are easy to recycle since they can be separated from the other plastics, but for plastics that originate from e-waste or composites, incineration is the preferred option. Moreover, the Swedish Environmental Protection Agency (Naturvårdsverket) together with the Swedish Standards Institute (SSI) has developed standards for plastic recycling aiming to be promoted internationally. This action will improve the acceptance of recycled plastics from both industries and the society since the quality of the recycled plastic can be now verified [Avfall Sverige, 2018]. Thermochemical recycling of plastic waste is attracting a lot of attention during the last years since a variety of research projects has been funded nationally [Moradin et al., 2016]. On the other hand, efforts for industrialization of alternative thermal waste treatment are minimum. Finally, garden waste is being treated by both biological recycling and energy recovery through pyrolysis. The latter is used in specific locations in Sweden with the main purpose of biochar production.

The environmental benefits of waste prevention and reuse of materials has been very well communicated and adapted by Swedish society. There are several acts and tools to promote these initiatives, for example websites ([www.milönär.se](http://www.milönär.se), [www.avfallsverige.se](http://www.avfallsverige.se), [www.ewwr.eu](http://www.ewwr.eu)) created by the waste association or EU in order to organize and map acts for reuse among the country, educating people for reuse and refurbish old materials and goods and communicate initiatives such as second hand markets [Avfall Sverige, 2018-2].

## 2.3 WASTE PRETREATMENT AND WASTE DERIVED FUELS

In this subsection, waste pretreatment as a prerequisite to becoming a feedstock for alternative thermal treatment is addressed briefly.

MSW is available in large quantities in most IEA Bioenergy countries. Despite being a heterogeneous solid fuel, its energy content can be utilized efficiently in state-of-the-art incineration plants, most of them applying grate firing technology. Concerning alternative thermal treatment technologies, it offers the advantage of not being burdened with elevated heavy metal, halogen or alkaline content compared to other waste streams like sewage sludge, electronic waste, or industrial hazardous waste streams. MSW pretreatment is a non-standardized process widely applied with the purpose of pre-sorting and recycling waste fractions. Typically, the process chain consists of coarse shredding, sifting, magnetic belt and eddy current separation as well as fine comminution. Ferrous and non-ferrous metals as well as coarse and fine mineral fractions are recovered separately. The major fuel-type product derived from MSW is refuse derived fuel (RDF), which is primarily targeted towards the purpose of combustion. An international standard for solid recovered fuel (SRF), which is a more strictly defined sorted waste, is under development (ISO/TC300). Waste pretreatment includes mechanical and/or biological technologies as well as manual sorting. Today, most RDF is burnt applying waste-to-energy incineration technologies. In an increasing number of EU countries, higher quality / higher heating value RDF replaces coal as fuel of cement plants. In the market, high volumes of waste-derived-fuels currently compete with cheaper fuels such as MSW, waste wood or residual biomass on limited WtE incineration capacities.



Figure 5: Certificated Solid Recovered Fuel (SRF) produced from biomass and household waste in the frame of the EU funded RECOMBIO project [Gehrmann et al., 2018]

Sensor-based sorting of especially packaging waste in automatized plants up to 100 kt/a capacity is widely applied in the countries mentioned above for sorting of separately collected packaging waste. It allows for often color specific recovery of pure non-compound plastic recyclates of quite high purity such as HDPE, LDPE, PS, PET and PVC. These pure fractions can be post-processed to regranulates of qualities as close as possible to virgin material. There is no standard for these secondary products, so far. Also mixed plastics of lower quality are recycled. In general, regranulates cannot achieve the quality of virgin material due to chemically bound ingredients such as ultra-fine particles affecting color and due to catalyst residues, and because of impacted mechanical properties because of reduced polymer chain length during post-processing. In addition to SRF preparation and separation of minerals and valuable metals mentioned above, state-of-the-art sensor based plastics sorting can be applied in principle to other fractions than separately collected packaging waste.

By its nature, MSW is very heterogeneous both physically and chemically. This causes operational challenges for alternative thermal conversion systems described below. In addition, the physical nature of waste complicates mechanical feeding into such systems. In order for MSW to be used in such systems, it usually needs pre-treatment to remove non-combustible materials, homogenized to minimize operational variations, and ideally transformed to a physical nature compatible with mechanical feeding systems.

A recent evaluation highlights that mechanical and mechanical-biological pretreatment of MSW can allow waste to meet the physical and chemical specifications required of alternative thermal treatment facilities [Stapf et al., 2019]. The pretreatment processes are relatively straightforward and involve several stages of sorting, separating, size reduction, and in some cases, biological treatment. Capital costs for the pretreatment systems are moderate and generally worth the benefit of making a low-cost, readily available feedstock stream available. Overall economic analysis is favourable, but viability depends strongly on received gate/tipping fees associated with collecting the municipal waste.

Specific thermal treatment technologies have different RDF or SRF quality requirements to be met by the pretreatment step. This will be referred to in the next section with the specific technologies.

### 3 Alternative Thermal Treatment of Waste

This section first gives an overview about recycling processes according to its physical or chemical nature, followed by three subsections on most important thermochemical recycling technologies and application cases.

This report mainly emphasizes processes and technologies capable of processing mixed wastes in a relevant industrial scale as indicated by a technology readiness level (TRL) of 7 (system prototype demonstration in operational environment) or higher. The base thermal waste treatment process is waste incineration (WtE), i.e. combustion of waste with sufficient oxidant to allow full conversion of the hydrocarbon content to CO<sub>2</sub> and water. For alternative thermal treatment (thermochemical conversion) we distinguish between sub-stoichiometric oxidant availability (gasification) and processes with no additional oxidant feed (pyrolysis).

**Gasification** is an established process for production of chemicals and liquid fuels from coal; however, its use to manage waste streams is much less developed. The desired gasification product is syngas (main products are CO and H<sub>2</sub>) of a specific composition depending on the downstream utilization process. Autothermal gasification in general delivers the necessary temperature level for a high syngas yield by direct heating, i.e. partial combustion of the feed, resulting in the byproducts CO<sub>2</sub> and H<sub>2</sub>O. Such as incineration in a one-step process, gasification processes can be applied to generate energy in combined heat and power plants (CHP). In comparison to incineration, this can be seen as a two-stage combustion process where the feed is gasified first and the syngas is burned afterwards to generate heat. It is also possible to utilize the syngas as a secondary feedstock which can be converted in downstream chemical synthesis to either “green fuels” or to basic chemical products—which demonstrates the flexibility of gasification pathways for waste management.

The definition of **pyrolysis** includes purely thermal cracking of the feedstock, catalytic cracking, and / or hydrocracking. In case of real mixed waste, it typically includes chemically bound oxygen, resulting in oxygen containing products such as water. Any pyrolysis process yields at least three multicomponent product phases, namely permanent gas, condensable vapours, and charcoal. Pyrolysis is an endothermic process that requires reaction heat supply through indirect heating of the reactor. It can be provided by means of combustion of part of the pyrolysis products. The purpose of pyrolysis is to convert biomass or mixed waste into secondary feedstocks for the production of fuels or chemicals. Due to the nature of the pyrolysis process, it cannot liquefy more than approximately 50 mass-% of the feed, depending on its composition and the pyrolysis conditions. Furthermore, the multi-phase nature of the product stream can see the need for additional downstream processes.

Fuels and chemicals synthesis from solid feedstock by means of gasification or pyrolysis demands high product quality to be used as secondary feedstock, in contrary energetic product utilization. Both, biomass and waste based synthetic fuels and chemical products are chemical energy carriers which can reduce greenhouse gas emissions by replacing primary fossil feedstocks. Making chemicals from waste is called “chemical recycling” or “feedstock recycling” and contributes to the closure of the carbon cycle and thereby to an increase in the rate of recycling, in particular of traditionally hard-to-recycle materials.

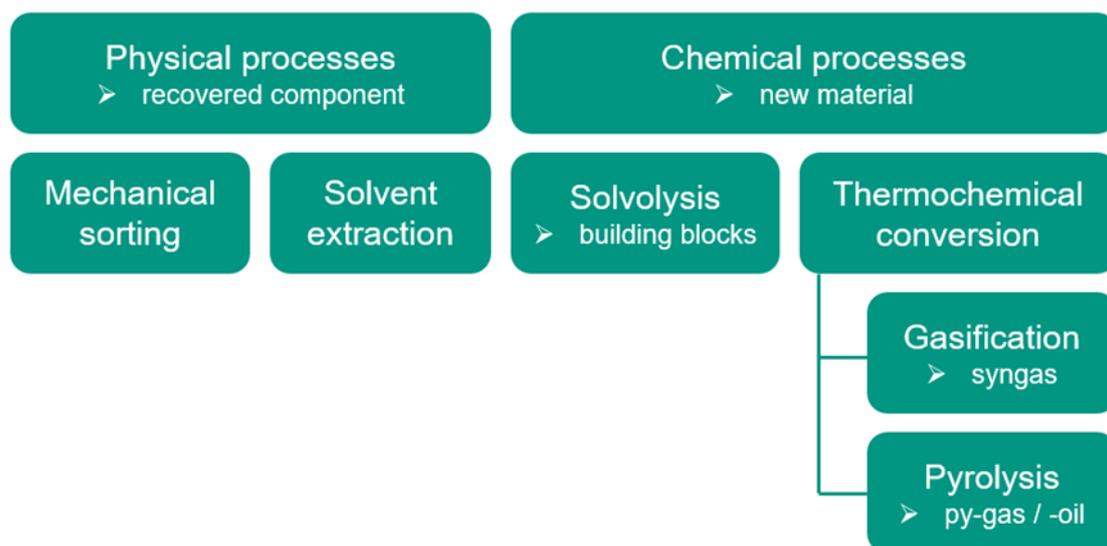


Figure 6: Recycling processes for mixed waste and their key products

The scheme in Figure 6 organizes recycling processes according to their either physical or chemical nature. Recovered components maintain their chemical nature during physical recycling processes (e.g. material recovery of a specific polymer), whereas chemical processes in general break up the initial material (e.g. recovery of the monomer as building block for new material).

**Physical separation processes** (mechanical treatment, see section 2.3, or solvent extraction) are well established technologies to separate valuables from waste mixtures. Higher plastic recycling rates can be achieved by broad application of sensor-based sorting technologies or in some cases by applying polymer type specific solvents. However, these technologies are characterized by high specific cost compared to basic mechanical waste pretreatment (crushing, screening, etc. aiming for metals and minerals). The long-term increase of eco-products ("design for recycling") will also lead to a higher rate of recovery in the packaging sector. Here the focus lies on physically separable thermoplastics. The polymer is recovered as so called recyclate and can be processed into new plastic products. An obstacle is the lower quality of these products compared to new products ("downcycling").

Solvolytic **chemical separation processes** have so far found only a small application, mainly applied to pure plastic waste streams available at plastic manufacturers or at plastic processing industry. This depolymerization through chemolysis is possible with polycondensates, mainly. The monomers are recovered from the mixture and can be re-processed to high quality virgin material. Key obstacles to increased adoption of this processing technology include contaminants of the feedstock and the high process-specific separation effort.

Non-selective solvent liquefaction applying a hot, pressurized solvent aims at breaking down the waste polymer structures primarily into liquid components of a slurry. Reaction conditions can be supercritical for the solvent. An example is hydrothermal liquefaction of biomass. Such as gasification and pyrolysis, it falls under the category of thermochemical conversion.

In general, **thermochemical processes** (Thermal conversion) of waste decomposes mixtures of substances at high temperatures into organic basic building blocks of chemistry, from which again new products of high quality are produced. During processing, metallic and mineral impurities are separated. In principle, thermochemical processes are also suitable for those waste fractions which cannot be sorted by the abovementioned processes, for example the non-pure fractions resulting from separate collection packaging waste such as sorting residues and shredder fractions. In general, mixed composite materials as well as plastics contaminated with catalyst residues or additives such as flame retardants are to be treated thermochemically.

When applying thermochemical recycling to mixed waste, the waste has to be pretreated to become a suitable reactor feedstock. Of particular importance are particle size distribution and ash melting point. These requirements are met by established mechanical pretreatment according to section 2.3. Herein, low-melting mineral components can be separated.



Figure 7: Process chain of the thermochemical recycling of wastes to secondary (chemical) feedstocks

Thus, the full process chain (see Fig. 7) usually consists of the (mechanical) pretreatment, the (thermochemical) conversion, and the cleaning (upgrading) of the respective main product. During the thermochemical degradation process, the heating rate, process temperature, stoichiometry, and residence time parameters must be optimized to maximize product yields and process reliability. Often, upgrading of the conversion products is necessary to meet the secondary feedstock specifications. Process chain by-products can be valuable substances (e.g. metals) or energy carriers (e.g. heat), as well as material streams to be disposed (e.g. ashes, wastewater). Process suppliers or operators just as the literature describe a

broad variety of methods and technologies for the feedstock recycling of waste at high process temperatures, which all fall under the categories of Fig. 6. A detailed listing including descriptions of the individual technologies with a particular focus on the alternatives for the incineration of municipal waste for energy utilization can be found in [Quicker et al., 2017]. Most technologies have not proven applicability in industrial scale over a longer period, so far. The technology Readiness Level (TRL) is relatively low. At this report, we refer to industrial applications (TRL 7 - demonstration system, TRL 8 - first of a kind commercial system, TRL 9 - full commercial application), or to a lower TRL (TRL 3 - applied research, TRL 5 - large scale prototype, TRL 6 - prototype system) in case of current efforts to bring a residual part of the recycling process chain into industrial scale. This is specifically the case for the important upgrading steps necessary to guarantee the qualities of the products for further use in process industry.

### 3.1 GASIFICATION FOR ENERGY UTILIZATION

Gasification in the context of waste management intends to convert biogenic energy resources and anthropogenic waste fractions (e.g. biomass, refuse-derived fuels, plastic wastes) into a high quality syngas containing the chemical building blocks  $H_2$  and  $CO$ . Syngas is an industrial feedstock used globally for (i) synthesis of transportation fuels (ii) integrated into a combined-cycle power plant (IGCC) production of electric power in integrated gasification combined cycle plants (iii) synthesis of chemicals and products for direct sales on the market. Option (iii) is important in the context of waste management and recycling—it is referred to as thermochemical recycling of waste by gasification and is discussed in the following section. Options (i) and (ii) are not regarded as recycling but as energetic feedstock utilization. Biogas, a mixture of  $CO_2$  and  $CH_4$  from biological treatment of organic waste, is not in the scope of this report.

Historically, gasification emerged as a subprocess of pyrometallurgy, where the oxidized metals and coke typically react to form the desired raw metals and lean gases, which are energetically used.

Dedicated gasification technologies became industrially relevant in the 2<sup>nd</sup> quarter of the 20<sup>th</sup> century in order to overcome dependency from petroleum imports. Both, mobile wood gas carburetors and industrial scale coke-based syngas generators were developed up to high TRL. Although not being competitive on the world market, coal based synthetic fuels were of specific relevance for closed economies such as in South Africa. So, significant capacities were installed and operated over a long period. This forms the basis for feedstock recycling of waste. The technological challenge of reliably producing clean syngas for fuel synthesis is similar to that of chemically recycling waste via gasification. A second development push for gasification technologies came from the oil crisis. Then, large scale high quality syngas production and high temperature gas cleaning were developed to feed gas turbines in ultra-efficient power plants of the integrated gasification combined cycle (IGCC) type. For reason of power market prices, most large scale demonstration plants have been closed.

So far, application of gasification to generate second-generation synthetic biofuels is at the demonstration scale. Here, highly developed gasification technology is applied to heterogeneous, pretreated feedstock closer to waste. Furthermore, attempts to generate more bioenergy based electricity has caused installation of some hundred small scale and easy-to-run decentralized gasifiers mainly in Europe during the past decade, but with lower overall process efficiency. Hydrothermal treatment of biomass is not of significant relevance, so far.

Waste gasification in industrial scale was developed in parallel feedstock utilization (see next section) and for energetic utilization as an alternative to state-of-the-art incineration technology. Whilst in most Asian countries, waste incineration capacities specifically for MSW dramatically increased during the past period in order to overcome environmental issues with growing waste amounts, negative perception of incineration technology in some European countries drove commercialization of alternative technologies. Specifically in the UK, high landfill charges in combination with promotion of alternative thermal treatment technologies led to recent gasification based WtE projects. In these mostly air-blown waste gasification applications, usually the carbonaceous products of the thermochemical process step are subsequently used energetically. Being applied as “two-stage combustion“, gasification process chains are more complex and less mature than best available incineration techniques, thus resulting in higher waste treatment costs.

An industrial waste-gasification reference is the 100 MW bubbling fluidized bed gasifier at the CEMEX cement plant in Rüdersdorf, Germany. The air-blown gasification of RDF provides the fuel gas for the calciner based on 100% waste feedstock which is not specifically pretreated for this purpose. The plant is in continuous operation for ca. 20 years now and allows the total cement plant to almost only run on waste based fuels. Yet, quality requirements of the syngas are moderate because of its energy application in a high-dust environment. This is a good demonstration of the flexibility that gasification pathways offer, not being limited to only the production of heat and power.

For more information, a detailed compilation on waste gasification is given in [Waldheim, 2018].

## Process and Technologies

Any combustible solid feedstock undergoes the consecutive physical and chemical conversion steps drying, evaporation, char gasification and gas-phase oxidization of combustibles during a thermal process with presence of an oxidant. Depending on the reactor-internal zonal segmentation and the intermediate product flows between the zones and the occurring conversion steps, final syngas quality can vary significantly. In the overall gasification process, sub-stoichiometric addition of oxidant will (theoretically) be sufficient to convert all char. In high-temperature gasification, relatively-clean syngas can be generated and thermodynamic equilibrium achieved by introducing additional oxidant; the price of this is the part of the feedstock needed for combustion to produce CO<sub>2</sub> and H<sub>2</sub>O. If lower process temperatures are applied, the synthesis gas yield is higher, but it contains problematic non-equilibrium components such as trace-gas species, residual methane and high-boiling hydrocarbons (tars). Here, experimental experience from literature has to be taken into account.

There are many design variants for industrial-scale gasification. For the gasification of carbonaceous solid fuels, fixed bed, fluidized bed and entrained flow gasification processes have been developed; the latter is also particularly suitable for (viscous) liquid feedstocks. As a rule, fixed bed gasifiers require coal as an additional feedstock when used on biomass or waste as they have bed structural requirements similar to those of a blast furnace. With regard to the achievable synthesis gas quality (residual methane and tar contents), entrained flow gasifiers are outstanding, fluidized bed gasifiers (circulating or stationary operated) follow thereafter and fixed-bed gasifiers (especially in counter-current operation) deliver the lowest qualities. Conversely, the pretreatment costs for feedstocks into an entrained flow gasifier is greatest, due to the fact that entrained flow gasification requires either liquid or pulverized solid feedstock at maximum grain size of approximately 0.1 mm. Fluidized bed reactors can accept up to 50 mm grain size and fixed bed gasifier's particle size distribution limits are even lower, but a significant part of the feed must show persistent physical and thermal stability form a stable matrix inside the reactor.

All three gasifier types mentioned above are scalable to the 100 MW size, but only entrained flow gasifiers can achieve the 1000 MW size due their high reaction density, specifically when they are pressurized. As proven technology, entrained flow gasifiers can operate at up to 80 bar, thus avoiding additional costly syngas compression up to the pressure level necessary for thermal separation technologies, chemical synthesis, or gas turbine fuels, and supporting very high throughput of feed with a relatively-small reactor volume. Usually, pressure levels of fluidized bed and fixed bed gasifiers are lower.

Today, industrially scalable entrained flow gasifiers dominate the market for new installations on fossil feedstocks used, and the use of fixed-bed gasifiers is decreasing. Fluidized bed gasifiers have little significance in industrial scale syngas production but a high number of small scale units have been recently applied to pure biomass for energy utilization, mainly.

Long-established metallurgical industry technologies are also used to gasify waste. These include the shaft furnace in the non-ferrous metals production and the blast furnace of raw iron production. A special form is the gasification in the limestone moving bed, derived from the lime industry. The particularly high process temperatures lead to the separation of the feed substances (molten separation of the metallic or mineral fraction). The process gas contains the hydrocarbons in partially oxidized form. Plastic waste in this case replaces part of the coke or the blow-coal and act as a reducing agent. The gas qualities are comparable to

those of fixed bed gasifiers. The operation of mainly waste is carried out only in the middle scale range for vitrification of the slags and for the energetic use of the synthesis gas, especially in Japan [Vehlow, 2016] and reached high TRL. The requirements on the quality of the waste and the permissible waste components are higher than those of the above-mentioned types of gasifiers, the raw gas qualities are lower due to the pyrolysis gas components contained, as well as are resource and energy efficiency.

Even higher temperatures are reached when the energy is provided electrically to generate a reactive plasma. Thermodynamically, there are only slight advantages in the gas composition over, for example, entrained flow gasification. The external energy consumption is particularly high. The application of plasma gasification has so far mainly been carried out on hazardous waste in small scale.

### 3.2 GASIFICATION FOR CHEMICAL RECYCLING

Gasification as part of a thermochemical recycling process aims at providing secondary feedstock from waste for C1-chemicals such as methanol and C1-based value chains such as Methanol-to-olefins. Syngas based fuel synthesis processes such as Fischer-Tropsch are not considered as recycling here; however, as they contribute to greenhouse gas emissions significantly when fed with natural gas, there is an opportunity for waste to contribute to emissions reduction in that sector, too.

Industrial gasification today mainly uses entrained flow gasification with many installations in the beginning of the 21<sup>st</sup> century for gasification of pulverized coal. All gasification developments of the 20<sup>th</sup> and beginning 21<sup>st</sup> were driven by local availability of cheap carbon rich feedstocks. Usually, these gasifiers are oxygen / steam blown in order to avoid nitrogen dilution in downstream gas processing plants and to increase process efficiency.

Large scale gasification of biomass for feedstock utilization plays a minor role so far due to low fossil feedstock prices and missing CO<sub>2</sub> certificate cost for carbon chemical products.

The first applications of gasification technologies for waste feedstock recycling were driven by attempts to recycle plastics in the late 20<sup>th</sup> century. Specifically in Germany, two industrial scale gasification technologies in the 100 MW scale were operated over a longer period with different wastes and mixtures of it in order to produce methanol. In both cases, existing technologies for lignite feedstock developed to overcome oil import dependency were adapted to process RDF resulting from MSW or even collected packaging plastic waste.

At the German Berrenrath plant, a High Temperature Winkler (HTW) gasifier was run on lignite, RDF and plastics using oxygen, steam, and CO<sub>2</sub> as gasification agents. This gasification technology is characterized by a higher freeboard temperature of approximately 950 °C above the bubbling fluidized bed at 10 bars. This causes a better syngas quality. With a heat load of 175 MW, it fed a 100 kt/a methanol plant. The plant was shut down after 10 years of successful operation in the mid 90s for economic reasons, mainly methanol prices.

At the Sekundärverwertungszentrum Schwarze Pumpe (SVZ) in Germany which was already co-processing waste, sewage sludge, and lignite in revamped fixed bed Lurgi gasifiers, for the first time a British Gas Lurgi slagging gasifier was installed in early 2000. Different types of waste were converted to syngas then in the BGL gasifier at 25 bars and fed a 100 kt/a methanol plant. The minor syngas quality issues of the fixed bed gasifier were overcome by the extensive complementary plant structure of this production site where significant tar quantities removed from the syngas served as feedstock for an entrained flow gasifier. SVZ operations were terminated in 2005 mainly for two economic reasons, (i) methanol production cost of this rather small dedicated production site were too high compared to world scale natural gas based methanol plants and, (ii) for mixed wastes and sorting residues SVZ had to compete with cheaper waste incineration because legal regulations accepted low collected plastic waste material recycling rates, then.

Both technologies, HTW as well as BGL gasifiers, could not be operated fully on RDF but required significant co-processing of char forming fossil feedstock, namely lignite, and waste, together. In addition, RDF had to

be pelletized before being fed to the gasifiers.

This is not the case for the Showa Denko gasification plant at Kawasaki, Japan, which has operated since 2004 with an increasing amount of pure collected and presorted olefinic packaging waste feedstock, which is pelletized on-site before being fed to the gasifier. Here, a 2-stage gasification process is used at 10 bar, which consists of a steam / oxygen blown bubbling fluidized bed step at temperatures below 800 °C, followed by an oxygen / steam blown slagging entrained-flow like step to guarantee excellent syngas quality at ca. 1500 °C. The syngas is then converted in a water-gas-shift reactor, and hydrogen is removed and fed as part of the feedstock to a world-scale ammonia plant. Due to its specific nature requiring a high process temperature and not making use of the feedstock carbon content, cold gas efficiency and economics of this process is significantly lower than for the aforementioned gasifiers.

At Edmonton, Canada, Enerkem has operated (since 2017) an RDF-to-methanol process. It is based on its own proprietary technology that has been developed over a longer period and in several projects and plants with different sizes. Further projects have been announced in various countries. Again, this process uses bubbling fluidized bed gasification technology and staged addition of oxidants. The fluidized bed is operated at below 700 °C due to the low RDF ash melting point, followed by a freeboard at higher temperatures to minimize tar formation. After flue gas treatment and recirculating of the tars to the fluidized bed reactor, a proprietary methanol-to-ethanol process is applied at a smaller scale. Reactor over-pressure and capacity are smaller than for the processes mentioned above.

A more detailed description of these last three waste-to-methanol processes can be found at [Waldheim, 2018].

In addition to dedicated gasification processes, also pyrometallurgical processes can be used to chemically recycle waste. Specifically in iron ore processing, plastic waste is used to replace part of the reducing agent demand. Constraints here are the waste feedstock ingredients that must not disturb raw iron or steel production. This excludes biomass and many plastic types. In blast furnace processes, collected and sorted polyolefinic plastic waste is used to replace part of the coke but not the charge of the furnace. This application of waste feedstock is state-of-the-art and is successfully applied at the Voest Alpine steel mill in Linz, Austria, for a long time. Feedstock utilization of the syngas coming from melting-type furnace processes mentioned in section 3.1 has not been applied so far due to the bad gas quality resulting in a gas high treatment and cleaning effort. Recent efforts aim at making chemical use of steel mill gases. Also, using lime shaft furnaces as waste gasifiers has been subject to R&D efforts. TRL of the latter processes is still low.

## **Cleaning of the raw synthesis gas**

Waste feedstock recycling by gasification requires an exceptionally high syngas quality due to the subsequent catalytical chemical synthesis processes. It is higher than that of IGCC applications of syngas in turbines for power generation. Nitrogen dilution as well as hydrocarbon content of the syngas has to be avoided such that the upstream gasifier has to be operated with oxygen or steam as gasification agent, similar to CHP applications. The raw synthesis gas coming from the gasifier must be purified and conditioned to meet the required specifications of e.g. methanol synthesis. In particular, the limit on concentrations of trace gases such as sulfur, halides and nitrogen-containing components are much lower than for combustion exhaust gases and particles must be substantially removed. Small and large-chain hydrocarbons must also be removed from the syngas. In addition, the H<sub>2</sub>/CO ratio must be chemically adjusted depending on the downstream process of interest.

Figure 8 shows the necessary process steps in the synthesis gas treatment chain. It contains heat recovery steps to enable an overall autothermal processing and high energy efficiency. Tar removal steps have to be integrated at specific condensation temperatures in order to manage plugging. This is the key technology issue which limits feedstock as well as load flexibility of the plant. Following removal of particulates by (for example) high temperature filtration, a water-gas-shift reactor is included to adjust the H<sub>2</sub> and CO contents adjustment over a suitable temperature range. Subsequently, this study considers a Rectisol type

multi component gas scrubbing, upstream. Finally, the compression is carried out to achieve the required methanol reactor pressure.

It has to be pointed out that this gas treatment and conditioning effort significantly determines the processing cost of waste feedstock recycling. Furthermore, raw syngas quality drastically depends on the gasification technology applied. Thus, the cost of raw gas treatment in the case of entrained flow gasification would be much lower than in case of fluidized bed gasification which ranks above fixed bed gasification. On the other hand, feedstock requirements of the gasifier and thus pretreatment cost vary with technology. Thereby, fluidized bed gasification with lowest requirements ranks above fixed bed gasification and entrained flow gasification. Furthermore, fixed bed gasification requires a stable coke particle reacting bed typically achieved by adding fossil coke to the waste feedstock.

Here, we consider fluidized bed gasification of MSW pretreated according to the standards of state-of-the-art RDF or SRF being proven technology. The gas conditioning step in contrary is on a lower TRL level.

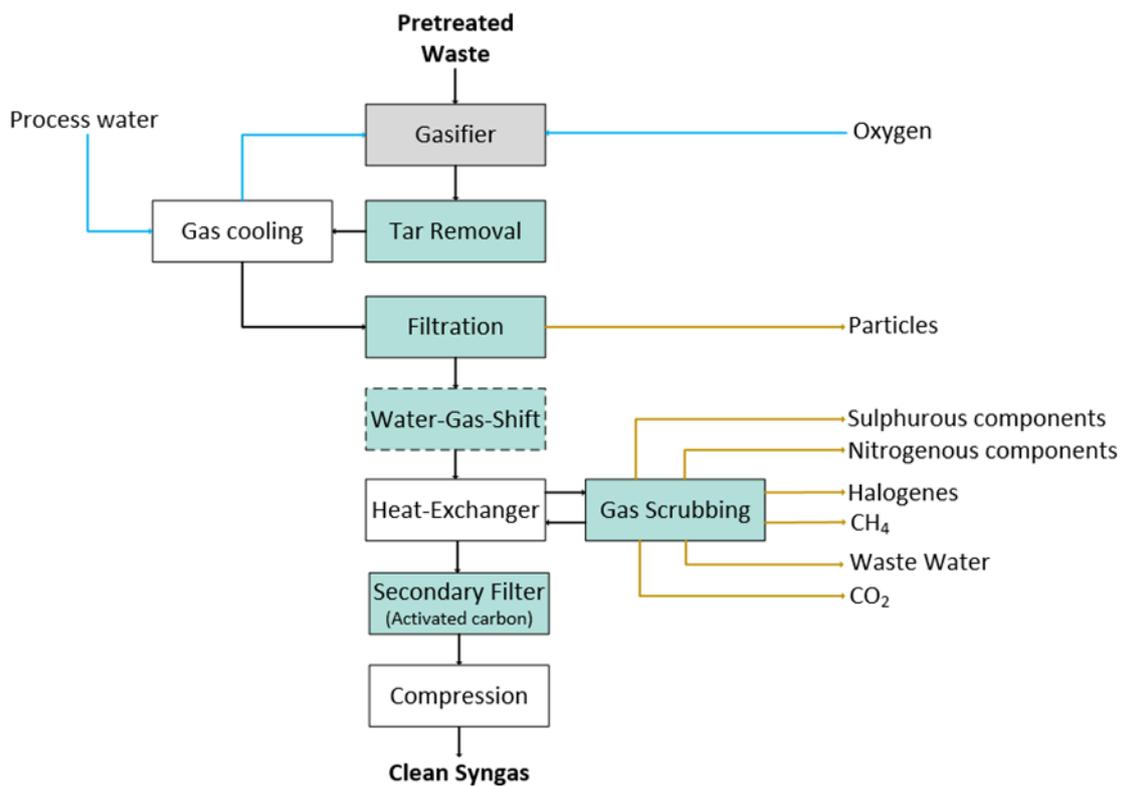


Figure 8: Major material flows and process steps in syngas production by gasification of pretreated waste

### Example case “Gasification of pretreated MSW in a fluidized bed gasifier and production of methanol syngas”

In the following, the results for feedstock recycling of pretreated residual household waste by gasification are shown by way of example, taken from [ABLC global, 2018, BKV-study, 2019]. Although, a similar fully integrated large scale process is operated by Enerkem (see above), detailed mass and energy balances that allow process evaluation have not been published so far. Thus, results shown here are based on process simulation.

Gasification processes can be modeled as thermodynamic equilibrium reactors under specification of the feedstock composition and incorporating heat losses. By adding oxygen or steam, the desired reactor temperature and syngas composition are reached with the highest possible theoretical cold gas efficiency. The cold gas efficiency describes the possible synthesis gas yield in terms of chemically bound energy, thus taking into account the effort to provide temperature by burning part of the feedstock.

In case of an oxygen/steam blown fluidized bed gasification of pretreated MSW considered here, the equilibrium balance was calculated at 950 °C. To consider the syngas tar content, experience from literature was taken into account.

Figure 9 shows the material flow diagram of this case. The overall process acts as a separation of substances, recovering the metallic value products, separating off mineral products, and recirculating carbon. The carbon mass-flow of the synthesis gas as desired recycled feedstock is significantly higher than the plastics carbon mass-flow of the waste. In the case of fluidized-bed gasification (Figure 8), about 1/3 of the initial waste mass is converted into synthesis gas. Based on the carbon used, it is about 46%. The remainder is converted to CO<sub>2</sub> during incineration of the mechanical pretreatment mineral fine content residue, furthermore to allow the necessary gasification process temperature, and in particular to adjust the required hydrogen content of the synthesis gas via the water gas shift reaction. In general, the synthesis gas yield of the waste gasification is higher than that of pure biomass gasification, since the latter contains less hydrogen. In the energy balance, which is not shown here, the thermochemical process part enables energy-independent operation of the entire process chain due to the supply of high-quality process heat, also taking into account the electricity requirement. The overall process energy efficiency of the chemical recycling process chain can achieve up to 90% by making use of both, gasification cold gas efficiency and high value syngas sensible heat.

In addition, we report total processing cost (capital plus operational) of this case. The processing costs related to MSW as input material amount to 21 €/t for the mechanical pre-treatment, 86 €/t for the thermochemical conversion and 105 €/t for the processing of the raw synthesis gas. The total cost of € 212/t is offset by revenues for the synthesis gas of € 68/t. For the case considered here, processing costs are particularly sensitive to the capital investment costs.

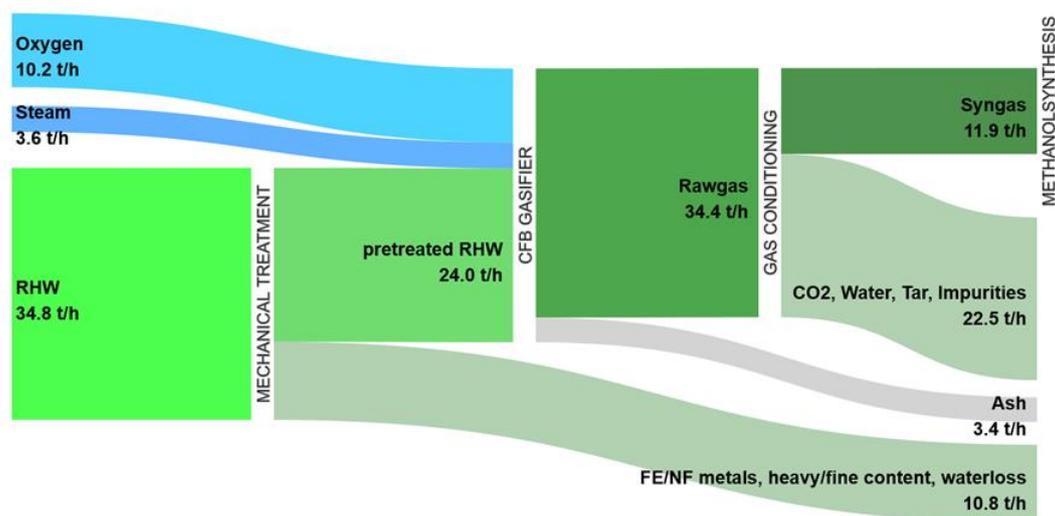


Figure 9: material flows in the process chain “fluidized bed gasification of residual household waste”. Heat load of the gasification step is 100 MW.

### 3.3 PYROLYSIS FOR CHEMICAL RECYCLING

Pyrolysis as a recycling process aims at the conversion of solid carbon from e.g. biogenic residues or plastic waste streams to supply process industry with easily accessible hydrocarbon feedstocks. Pyrolysis is a non-equilibrium process controlled strongly by reaction kinetics and heat and mass transfer. Thus, product distribution depends on both, the feedstock used and the reaction conditions such as temperature, heating rate and residence time. Pyrolysis was the first dedicated thermochemical process besides combustion. It evolved primarily to the production of coke from wood or coal. Left over from this pre-crude oil age are two industrial scale applications:

- The coking plant providing coke from hard coal in large fixed bed furnaces operated batchwise supplies the pyrometallurgical industries. The solid yield is high due to the feedstock. By-products (coal tar and coke oven gas) are mainly used energetically.
- The production of charcoal from wood with a yield typically not higher than 50 wt-%. Usually, hard wood is pyrolyzed in batch processes in fixed bed reactors. As byproduct, vapors are condensed and thermally separated to yield e.g. acetic acid and tar oils. Quite few such applications worldwide supply the charcoal market.

In addition, there are some industrial scale petrochemical applications operated continuously such as those designed for pyrolysis of oil sludge in a rotary kiln. Most large scale coking processes in refineries are operated with oxygen carrying gases such as steam, thus not strictly falling under the pyrolysis category defined above.

In recent times, pyrolysis was developed further to have a range of applications to various feedstocks and purposes. Examples are the liquefaction of lignocellulose for the production of substitute fuels and the pyrolysis of residual household waste for energy utilization. Rotary kilns, auger type reactors and fluidized bed reactors are applied in order to continuously operate the processes.

Fast pyrolysis has been investigated extensively during the past decades for the purpose of direct thermochemical liquefaction of sustainable biomass. Resulting bio-crudes and bio-oils are upgraded to bio-fuels or bio-chemical intermediates e.g. by means of hydrogenation. So far, little commercial application appeared mainly in the non-transportation fuel sector. IEA Bioenergy (2016) provides an overview on globally installed thermal liquefaction capacities in demonstration scale. The use of alternatives to waste incineration is not driven by feedstock utilization: usually the carbonaceous products of the thermochemical process step are used energetically such as for most gasification processes. Thus, in the process chains, important upgrading or product cleaning steps are missing, which are necessary to guarantee the qualities of the products for feedstock utilization in process industry and therefore the concept of ‘plastic recycling’ of interest here. While often attractive due to the seemingly-simple upfront capital requirements, pyrolysis is more complicated when the entire process chain is considered, and therefore is less mature than best available incineration techniques.

One of the few examples of pyrolysis that has been operated successfully on industrial scale for a significant period was the MSW pyrolysis plant at Burgau in Germany (1983-2016). MSW and sewage sludge were pyrolyzed in two rotary kiln lines of ca. 2 t/h capacity each, followed by combustion of the pyrolysis gases and vapours in a steam boiler. According to [Quicker et al., 2017], electrical efficiency of the plant did not exceed 22% due to the high amount of char in the solid residues. The plant was finally shutdown because of missing economics due to low electricity revenues as well as the high disposal cost of the solid residues.

Further successful operational cases for this kind of technology making use of the pyrolysis products energetically are documented for Japan [Vehlow, 2016]. In Japan, separation and melting of the slag was in the focus of MSW treatment for a long period due to legal requirements. This encouraged application of thermal treatment technologies alternative to incineration on the grate although energy efficiency and economic performance of the alternatives was worse.

A mature example for chemical recycling of waste by pyrolysis is the end-of-life tire pyrolysis facility at Hirohata steelworks in Japan that serves as a blueprint for recently planned tire pyrolysis plants in Europe. Operating since 2004 with a capacity of ca. 4 t/h in each of the two rotary kilns, shredded waste tires are processed to different valuable products: pyrolysis gas, light and heavy pyrolysis oil, carbon black, metals, and a mineral residue [Zorbach, 2017]. Whilst the latter is deposited and the pyrolysis gas is energetically used to balance the heat demand of the pyrolysis plant, the other products are used in the steel plant as reducing agents and as carbon feed for metal recycling. Chemical grade quality of pyrolysis gases and condensable vapours is not in the focus of this process.

Recent activities on chemical recycling of waste by pyrolysis all focus on plastic waste. As plastic waste streams can be less heterogeneous than unsorted MSW, this does have some advantages over whole-MSW

applications. Driven by the first EU plastics strategy [COM(2018)] which sets mandatory recycling quotas for the EU countries, plastics producing industry and waste management companies announced several ambitious projects which will lead to capital investment into plastics liquefaction. Main purpose is to recover end-of-life plastics as petrochemical liquid feedstock. So far, only two plants in Almeria and in Seville in Spain operated by Plastic Energy Ltd. fulfil this task in a commercial scale. Both prefer non-contaminated polyolefinic feedstocks that amongst others are almost free of chlorine, biomass, etc.

## Process and technologies

As laid out above, the waste streams available at industrially-relevant quantities for chemical recycling are not the pure, sortable plastics that are often amenable to pyrolytic processes but sorting residues being mixtures of anthropogenic products and biomass. Pyrolysis of these waste streams is more troublesome, and the subject of research and development. Alternatives to rotary kiln technology have to be considered in order to homogenize pyrolysis reaction conditions and to optimize high value product yields adapted to the respective waste feedstock. Whilst accepting heterogeneous feedstock of quite large particle size and thus being the most flexible continuous high temperature reactor type, technological challenges of operating a rotary kiln under pyrolysis conditions include the drum seals and plugging of the inner drum especially in the case of higher feedstock plastic content.

Current R&D efforts aim at increasing the technology readiness level of these pyrolysis processes in order to improve economics of waste pyrolysis. In the case of pyrolysis, the technological challenges are the adjustment of product specifications on the one hand in-situ in the reactor, on the other hand by post-treatment, and in managing the plugging or sticking tendency of the intermediates within the reactor and in the downstream gas treatment and condensation steps. Large scale solid or moving bed, rotary kiln or fluidized bed reactors can be used, characterized by different mixing and heat or mass transfer behaviour. As references for waste pyrolysis, the few examples mentioned above are not sufficiently documented to allow balancing and independent evaluation.

Figure 10 shows the material flows of the integrated pyrolysis process considered here. The product distribution of solid, condensable and gaseous mixtures depends on feedstock, reactor type, and reaction conditions. In the case of the waste mixtures containing biogenic fractions which are considered here, aqueous condensates of low calorific values cannot be avoided. The condensable organic components are the valuable product that must fulfil the product specification as secondary chemical feedstock. A key issue is the removal of contaminants such as halides from the process flow in the reactor. Therefore, either sorbents are added to reacting mixture or pyrolysis gases and vapours have to be treated. Also, extensive post-processing of the liquid pyrolysis products by e.g. hydrogenation can be necessary to adjust the liquid hydrocarbon composition in the condensable pyrolysis products. Permanent gases and aqueous fluids are burnt to enable the autothermal operation of the overall process. Carbon containing solid products can be burnt for this purpose, too. Residual mineral fractions have to fulfil landfilling requirements. As the permanent gas might contain valuable hydrocarbons to a large extent depending on feedstock and process, it might be considered for feedstock utilization, too.

## Example case “Rotary kiln pyrolysis of pretreated MSW”

So far, industrial examples of feedstock recycling of waste based on pyrolysis are not sufficiently documented in order to be evaluated at a detailed level. Whilst the pretreatment and the pyrolysis step for MSW are on higher TRL level, delivery of chemical grade products by suitable reactor operation combined with industrial scale upgrading are not. So, the evaluation a full industrial scale process chain anticipates future successful technology development. In the [ABLC global, 2018, BKV-study, 2019] cited here, the expected product composition from pyrolysis of MSW was derived from literature data. Capital investment and operating expenditures were estimated based on reference plants of similar technology but different feedstock and operating parameters.

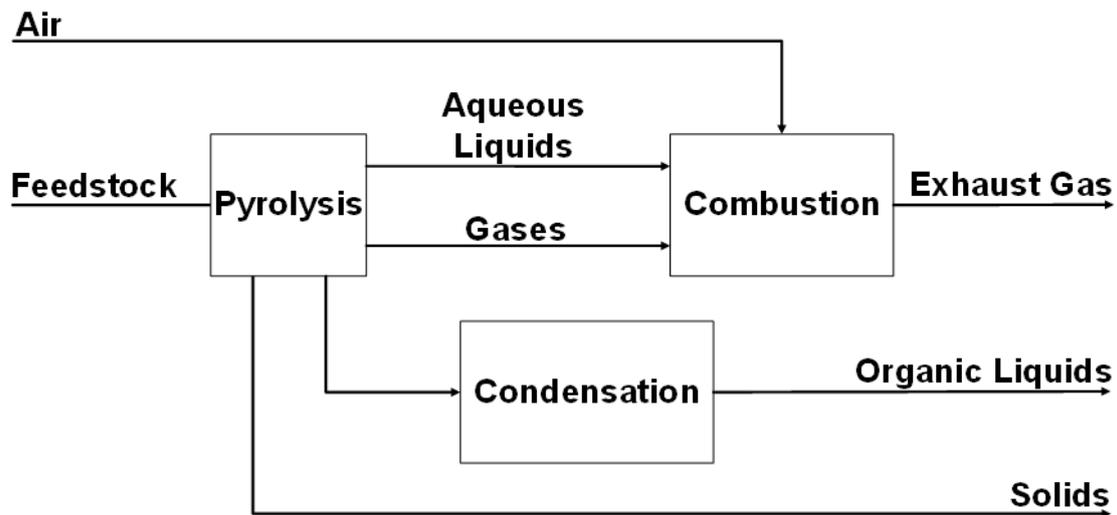


Figure 10: Major material flows and process steps in liquefaction of pretreated waste via pyrolysis

In the application of pyrolysis to pretreated MSW (Fig. 11), about 17 wt-% of the originally untreated feedstock is chemically recycled to the target product organic feedstock. Since these are hydrocarbons with low oxygen content, the carbon recycling rate here is about 45%, very similar to that of gasification processes. Separation and recycling of metals are also similar.

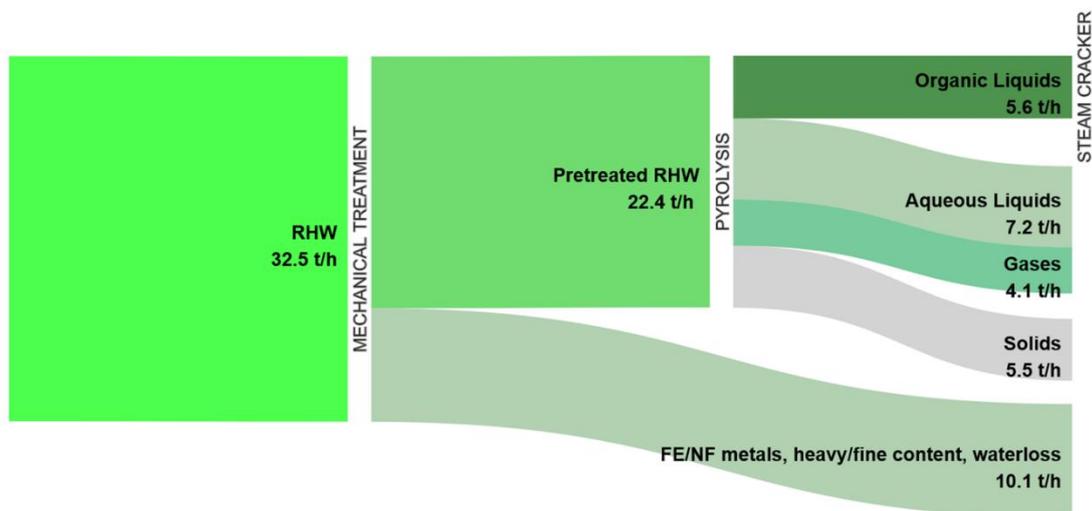


Figure 11: material flows in the process chain "rotary kiln pyrolysis of residual household waste". Heat load of the pyrolysis step is 100 MW.

The process costs are 21 €/t for the mechanical pretreatment (same requirement for the input material quality as CFB gasification) and 162 €/t for the entire thermochemical conversion process. The process integrated pyrolysis reactor according to Fig.11 acts as a separation step for the mineral content and the different product fractions. Therefore, product upgrading is not reported separately. The total processing cost of 183 €/t is partly compensated by revenues resulting from the pyrolysis oil of 86 €/t. The cost sensitivities are analogous to gasification processes. Thus, the results indicate that mechanical pretreatment of MSW followed by chemical recycling of the carbon containing residues at industrial scale might show total cost similar to current European gate fees for waste incineration. Unfortunately, technology readiness for mixed waste chemical recycling is yet insufficient.

## 4 Conclusions

Promoting alternative thermal waste treatment technologies such as pyrolysis and gasification goes along with waste management system optimization for the overall aim to reduce greenhouse gas emissions and to minimize the environmental impact. Declining social acceptance of incineration in combination with subsidies are drivers to invest into alternative thermal treatment, along with an increasing demand for recycled feedstock and a limited ability to physically separate more.

Current key drivers for developing and deploying alternative thermal waste treatment technologies are (plastic) waste recycling quotas in combination with perception about (marine) littering. Long term stable waste management systems are impacted by the demand to increase specific waste collection and sorting instead of energy recovery or even landfilling. Such systems support advanced alternative thermal waste treatment by providing a market of suitable feedstocks and by requiring chemical recycling of difficult-to-sort residues. Due to the mixed waste structure and behaviour, achieving the desired recycling quota and promoting circular economy for carbon in the mid-term requires both, waste collection and mechanical sorting systems, and chemical recycling of waste. Chemical recycling complements mechanical sorting by overcoming the downcycling issues of mixed materials and by avoiding final incineration of large amounts of separately collected wastes. Combined mechanical and chemical recycling thus maximizes the recycling rate and minimizes the greenhouse gas emissions. For this, thermochemical processes pyrolysis and gasification are thermal separation processes for mixed wastes including plastics, biomass and mineral fractions.

Whereas sorting technologies are ready to be implemented in order to increase waste recycling, thermal technologies for chemical recycling still need R&D efforts specifically concerning the flexibility to process varying complex mixed feedstocks and the scale of processing. Alternative thermal waste treatment technologies applied to WtE are mostly not competitive with waste incineration due to higher process complexity / specific capital investment. In contrary, pyrolysis and gasification processing cost come into the order of magnitude of waste incineration gate fees when being applied to complex waste feedstock recycling because of the recycled product revenues. By this, alternative thermal treatment of waste seems economically feasible and supports the transition to a Circular Economy.

Waste management system design and optimization is best supported by extensive methods like life cycle assessment, which shall be technology-neutral and strive for a suitable combination of technology approaches in order combine resource efficiency and energy efficiency to achieve the global sustainability goals. Concerning alternative thermal treatment of waste, the technological foundations are good and there are emerging drivers, but the overall economics are not competitive compared with less environmental and climate friendly waste management options. Therefore, targeted R&D is needed in parallel with the development of policy incentives to allow these technologies to emerge.

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