PLASTIC WASTE TO ENERGY AND FUEL: AN ANALYSIS OF THE TECHNICAL AND COMMERCIAL STATE OF THE ART

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LIST OF ACRONYMS AND SYMBOLS

EoL	End of Life
EPS	expandable polystyrene
HDPE	high-density polyethylene
LDPE	low-density polyethylene
PET	polyethylene terephthalate
PE	polyethylene
PMMA	polymethyl methacrylate
PP	polypropylene
PS	polystyrene
PU	polyurethane
PVC	polyvinyl chloride
R&D	research and development
RDF	Refuse-Derived Fuel
RPF	Refuse Paper and Plastic Fuel
WtE	Waste to Energy
WtF	Waste to Fuel
h	hour
t	tonne (metric)

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EXECUTIVE SUMMARY

- Plastics are an indispensable part of our modern world, serving as versatile materials in a plethora of industries, such as packaging, healthcare, and technology, contributing to convenience, durability, and efficiency in numerous applications.
- Addressing the environmental impact of plastic waste has become a pressing global concern, calling for immediate action via efforts to develop sustainable alternatives and recycling solutions.
- At the same time, our world currently faces a global energy crisis, which urgently calls for a transition to sustainable and efficient energy sources, to ensure long-term energy security and mitigate climate change.
- Both these grand challenges can be addressed employing Waste to Energy (WtE) and Waste to Fuel (WtF) technologies for creating valuable resources from the vast amount of existing post-consumer plastics.
- The purpose of this report is to provide a detailed analysis of the current state of the art of WtE and WtF technologies applicable to plastics, both from a technical standpoint, as well as from a commercial point of view.
- The technical state of the art analysis shows that numerous WtE and WtF technologies are currently available, which overall show promise in reducing plastic pollution and generating energy.
- The various technologies are at different levels of maturation, ranging from processes that have demonstrated their potential in the laboratory- and pilot-plant scale, to processes that are widely employed in industrial scale.
- Overall, challenges such as scalability, cost-effectiveness, and environmental impact largely remain, indicating that the field is still evolving. Continuous R&D innovation are essential to further mature these technologies and address their current limitations.
- The commercial state of the art shows that the commercial landscape of plastics WtE and WtF technologies has been evolving, with several companies globally exploring and investing in these solutions.
- However, the commercial viability and widespread adoption of these technologies may still face economic and regulatory challenges.
- Given the increasing emphasis on sustainability, it is likely that the sector will continue to grow and attract investment in the pursuit of more efficient and economically viable solutions.

1. INTRODUCTION

1.1 Plastics: what are they and what are they used for

Plastics encompass a very broad range of synthetic or semi-synthetic materials, the main ingredient of which are polymers, long chains of repeating molecular units. Plastics take their name from their plasticity (i.e., the ability to be easily shaped), which enables these materials to be moulded, extruded, or pressed into solid objects with different shapes, cast into films, or drawn into filaments. This key feature, along with other advantageous properties, such as being lightweight, durable, flexible, and inexpensive to produce, has resulted in the widespread utilisation of plastics[1]. In fact, no one could imagine a world without plastics today, despite the fact that their large-scale production and utilisation was not a reality before the 1950s. The rapid growth of the plastics industry, continuing up to now, is remarkable, with plastics surpassing most other synthetic materials[2].

Many common plastics are made from hydrocarbon monomers, however, other elements can also be involved in the various constituent polymers, such as oxygen, chlorine, fluorine, and nitrogen. Examples of common commodity (**Figure 1**) and other plastics alongside with some of their common applications are briefly discussed in the following. Polyethylene terephthalate (PET or PETE) is a dimensionally stable and easily machinable thermoplastic that is clear, tough, and solvent resistant. It is frequently present in beverage bottles, microwavable trays, and fibres for clothing, as well as engineering plastics. High-density polyethylene (HDPE) is a lightweight plastic with excellent chemical resistance and gas and moisture barrier properties, which make it ideal for beverage and other food containers and plastic bags. Low-density PE (LDPE), a soft and flexible plastic is commonly employed for bottles, shrink wrap, and wire and cable applications. Polyvinyl chloride (PVC) is a high corrosion- and chemicals-resistant polymer with long-term stability that is commonly utilised for pipes, fittings, floors, and windows, as well as in cable sheathing and medical tubing. Polypropylene (PP) is an economical thermoplastic showing high corrosion, abrasion, and impact resistance, which is commonly used in packaging applications

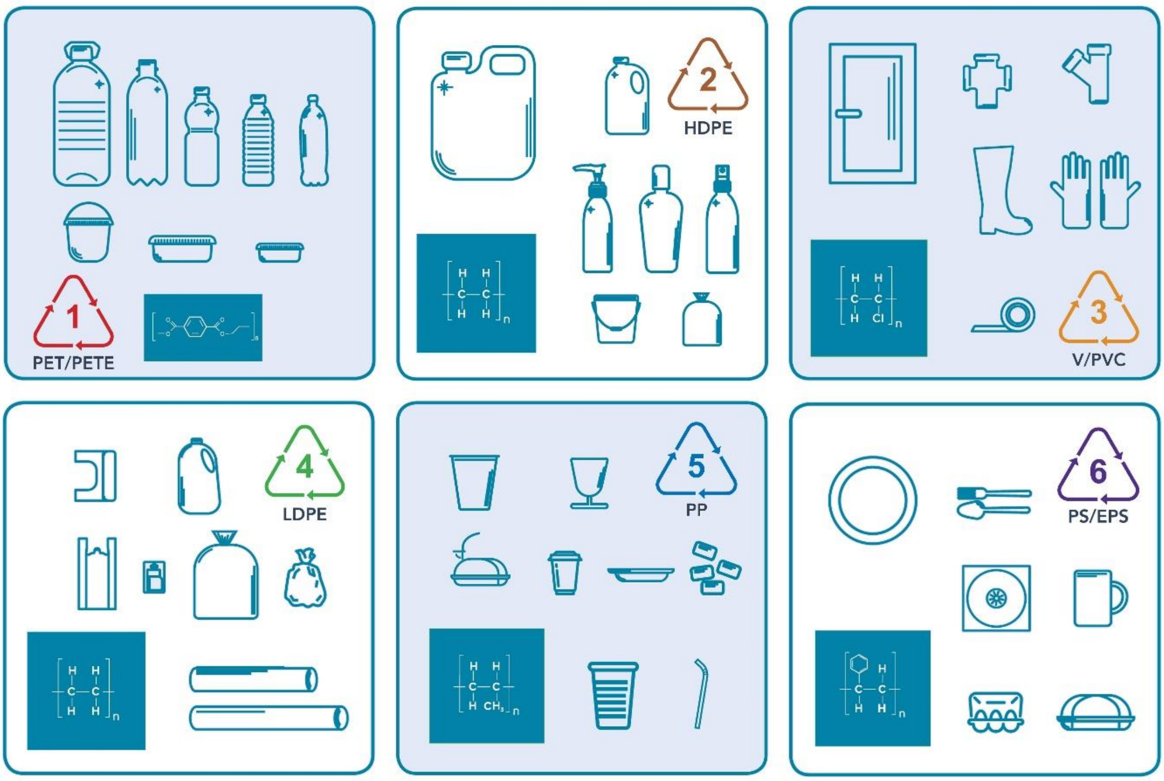

Figure 1. Examples of some common commodity plastics and their uses. The chemical structures of the constituent polymers and the corresponding recycling codes are shown. Adapted from reference[3].

and a plethora of other applications like fibres for fabrics and large moulded parts for automotive products. Polystyrene (PS) is a versatile polymer that, in its rigid form, is clear, hard, and brittle, finding applications in medical and food packaging, plastic cases, and others. Expandable polystyrene (EPS) is often extruded into sheets for thermoforming into trays for meats, fish and cheeses, and into containers like egg crates. Other plastics include *engineering plastics* (providing better mechanical and thermal properties than commodity plastics, e.g., polyurethanes (PU), polyamides, polycarbonate), *bioplastics* (including bio-based plastics made from renewable sources, e.g., polylactic acid and biodegradable plastics that decompose by naturally occurring microorganisms, e.g., polycaprolactone), as well as plastics from construction and demolition activities[1,3].

1.2 Challenges and opportunities associated with plastic waste

Although more recent industrial methods make use of raw materials derived from renewable sources like corn or cotton, the vast majority of today's plastics are manufactured using fossil-based raw materials like oil and natural gas[1]. Due to their nature, the constituent polymers are more often than not non-biodegradable. Consequently, the used materials accumulate, instead of decomposing, in landfills or in the natural ecosystem. A recent study estimated that 8,300 million metric tons (*t*) of virgin plastics had been globally produced up to 2017. As of 2015, approximately 6,300 Mt of plastic waste had been generated, with around 9% of this amount recycled, 12% incinerated, and 79% gathered in landfills or the natural environment. Considering current production and waste management trends and assuming that they will continue like this, it was foreseen that around 12,000 Mt of plastic waste will be in landfills or in the natural ecosystem by 2050. This *near-permanent contamination* of the natural environment is a serious concern calling for immediate action[2] (see **Figure 2**).

In addition to the pressing challenge of plastic waste disposal, another critical issue at a global scale is the *energy crisis*. The main energy sources for transportation (which accounts for one third of the global energy produced), such as coal, oil, and natural gas are non-renewable. These fuels are being consumed at an alarmingly high rate throughout the world, with the global supply of fossil fuels predicted to be depleted within 40-70 years, at the current consumption rate[5].

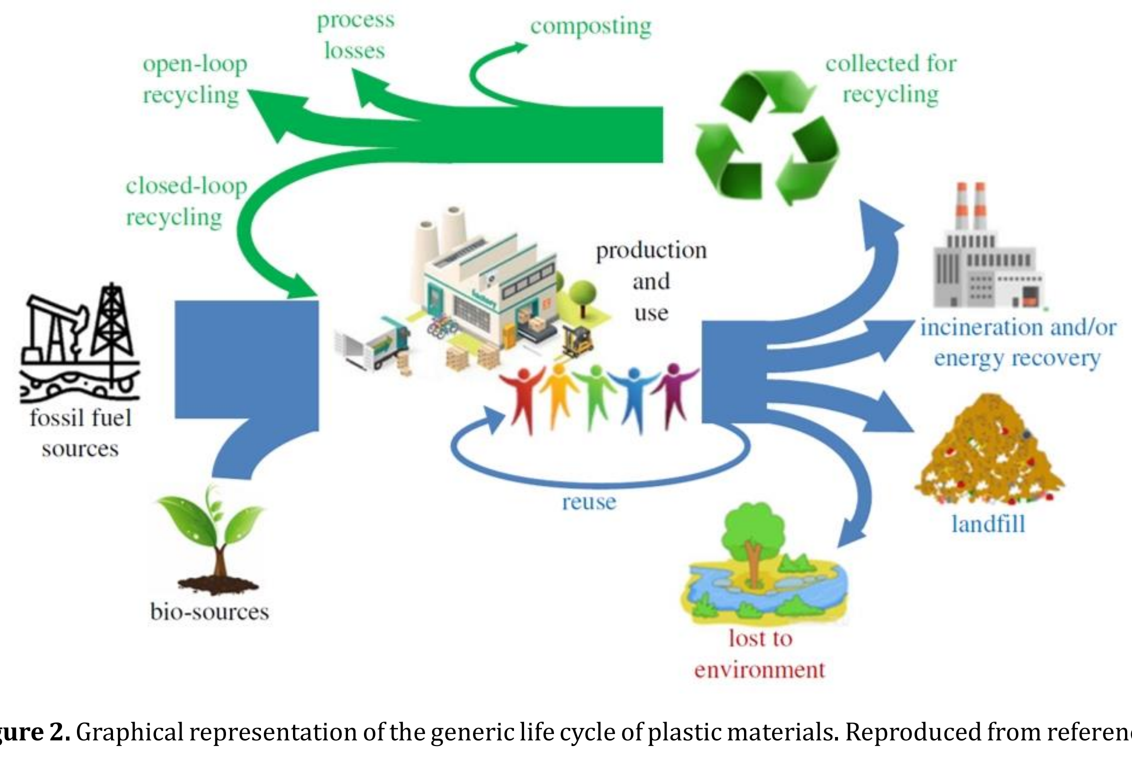

Figure 2. Graphical representation of the generic life cycle of plastic materials. Reproduced from reference[4].

The challenges of plastic waste management and the ever-increasing demand for energy can be both tackled by various End of Life (EoL) options for plastics that have been proposed up to now. EoL options (see **Figure 3**) generally include strategies and technologies that target the *reuse* of consumed plastics (at the level of material, component, or product), the *recovery* of useful products from used plastics (these products include both materials and energy), as well as the *disposal* of plastic waste (which includes both controlled methods like landfilling and uncontrolled ones like littering). In addition to traditional EoL recovery routes (e.g., incineration), novel EoL strategies have emerged in the past decade that aim at promoting the circular economy of plastics[6]. EoL options that target the recovery of materials and energy from plastic waste are the topics of discussion of the following two sections.

1.3 Plastics waste valorisation routes targeting recovery

Mechanical recycling is a way of making new products out of unmodified plastic waste, which was developed in the 1970s and is currently widely employed around the globe. Mechanical recycling typically starts by sorting the plastic waste and removing unwanted impurities, followed by processing (e.g., pulverisation, extrusion, washing) to make flakes or pellets. These forms are then utilised as raw material to make new plastic products[7]. The advantages of mechanical recycling, such as the relatively low cost and the associated reduced quantity of CO_2 equivalents, place it high in the hierarchy scale of waste recycling process[8]. However, recycling strategies that are highly successful for other commodity materials are often inadequate for plastics waste streams. From the 1980s onwards, the percentage consumed plastics that has undergone mechanical recycling has been less than half that of other materials. This is mostly because it is difficult to maintain processing and performance properties in the recycled product. Mechanical recycling relies on heating plastics to enable polymer flow through reforming operations (e.g., extrusion) to yield secondary raw, polymeric materials. First, heterogeneous waste streams do not show the same flow behaviour at the same temperatures, while non-plastic contaminants may interrupt machinery and affect the quality of the recycled product. Furthermore, the recycled polymers often experience thermal and mechanical degradation, either during their original use or during recycling; these altered properties can affect the processing equipment as well performance[9].

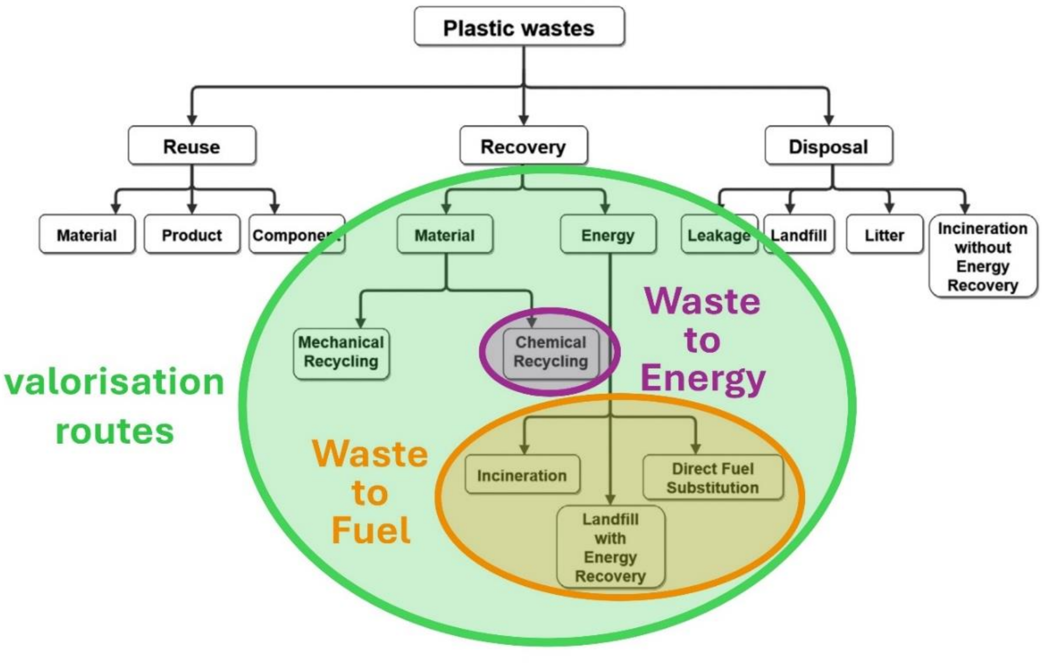

Figure 3. Synopsis of possible End of Life options for plastic waste, in which Waste to Energy and Waste to Fuel valorisation routes are highlighted. Adapted from reference[6].

Chemical recycling encompasses technologies that always involve the alteration of the basic polymer structure of the plastic raw material processed, via one or more chemical reactions, resulting in the production of smaller feedstock molecules. We must note that, often, chemical recycling only refers to processes that yield chemical or monomer feedstocks, which are then polymerised back into new plastics. If the latter is not the case, the process is termed *feedstock recovery*[8]. In any case, virgin-quality raw materials (i.e., building blocks) are provided to the plastic supply chain, which in turn allows for producing high quality polymers, such as food-grade plastics from post-consumer waste. Besides this advantage, chemical recycling represents an advantageous alternative to landfilling and incineration for polymer products that are challenging to recycle (e.g., by mechanical means), for instance films, multi-layered and laminated plastics[10].

Energy conversion, (also referred to as *thermal conversion* or *thermal recycling*) technologies process plastic waste at high temperatures and yield energy either directly (e.g., in the form of heat that can in turn be used to drive turbines and produce electrical energy) or indirectly (e.g., in the form of fuel oil or gas). These technologies are highly useful for processing waste with low moisture content and high concentration of non-biodegradable organic materials, such as plastics[11]. Energy recovery technologies can be viewed as complementary to other types of recycling, enriching the toolkit of solid waste management, not only by providing useful products like energy but also by reducing landfill waste and decreasing greenhouse gas emissions[12].

1.4 Plastic Waste to Energy and Waste to Fuel

To maintain the value of plastics even after their use, plastic waste needs to be converted to valuable energy or fuel; this is achieved by the following two types of strategies (see **Figure 3**). *Waste to Energy* (WtE) includes processes and technologies that focus on directly recovering energy for plastic waste streams, for instance in the form of heat (which can be in turn used to generate electricity). Examples of WtE technologies include incineration (based on the combustion of materials to generate heat and gasification (converting solid waste into a synthetic gas that can then be used to produce electricity or converted into fuel), which are discussed later in detail. *Waste to Fuel* (WtF) is a related concept that encompasses technologies that chiefly aim at producing fuels from plastic waste. Examples of WtF technologies include pyrolysis (breaking down polymers into various smaller molecules, including substances that serve e.g., as liquid fuels) and Refuse-Derived Fuel generation (producing solid fuels along with byproducts like ash).

Many plastic materials that are heavily used currently comprise polymers possessing calorific values comparable to the ones of crude oil derivatives, making waste plastics a raw material with significant potential for energy recovery. For example, the calorific values of PE (43.3-47.7 MJ/kg), PP (42.6-46.5 MJ/kg), and PS (41.6-43.7 MJ/kg) are very close to those of regular fuels like gasoline (46 MJ/kg) and petroleum (42.3 MJ/kg), indicating that the associated plastics are the most suitable for energy recovery. On the contrary, other common polymers such as PVC, PET, and polyamides have much lower calorific values, rendering these materials unsuitable for energy recovery e.g., by incineration. In some cases, dangerous byproducts can be also generated, e.g., PVC can yield HCl that is toxic and can also corrode the processing machinery[13].

Besides energy recovery, waste plastic can be converted to fuels that are clean and have similar characteristics to fossil fuels. For example, when considering the conversion of polyolefins (e.g., HDPE, LDPE, PP), the absence of oxygen and the high content carbon and hydrogen allows for avoiding further upgrading. No water in the plastic fuels makes the calorific value very high ,and the absence of oxygen makes the fuel non-acidic and non-corrosive, oppositely to biofuel. These features make the conversion of such plastic wastes to oil a growing field of study of high importance, which can potentially help alleviate the current energy crisis[5].

1.5 Structure of the current analysis

The present document is structured as follows. After this introduction, **Chapter 2** analyses the technical state of the art of technologies used for converting plastic waste into energy and fuels. This analysis begins with a detailed classification of the existing WtE and WtF technologies for plastic waste (**Section 2.1**), which is a prerequisite for understanding, optimising, and implementing effective waste management strategies. In **Section 2.2**, the first broad technology class, chemical recycling, is described. The second broad category, thermal recycling technologies, is the topic of Section 2.3. For the purpose of completeness, the chapter finishes with a brief reference to other recycling technologies that are currently not optimal for treating plastic waste (**Section 2.4**). **Chapter 3** is concerned with analysing the commercial state of the art of current WtE and WtF technologies for plastic waste. **Section 3.1** lists a number of interesting companies that are active in the WtE and WtF sectors, while **Section 3.2** describes the current status of these enterprises, key partnerships they have stablished, and significant investments having been made. Finally, instead of a part with concluding remarks, the key take-home messages of this report are summarised in the executive summary provided in **page 6** of the present document.

2. TECHNICAL STATE OF THE ART

2.1 Categorisation of plastic Waste to Energy and Waste to Fuel strategies

It is commonly accepted that WtE and WtF routes for plastic waste are powerful strategies, not only for providing (direct and indirect) alternative sources of energy that are economically viable and environmentally sustainable, but also for lowering the environmental impact compared to traditional waste disposal methods. It is important to categorize the plethora of existing WtE and WtF technologies due to several reasons, primarily related to understanding, optimising, and implementing effective waste management strategies. First, different waste streams and materials (even within the already narrowed down range of plastics) may require distinct processes for efficient conversion into energy or fuels. Categorisation enables one to identify *suitable technologies* based on the very characteristics of the waste in question. Second, it allows for developing specialised, *optimised processes* tailored to specific types of wastes. This is crucial for maximising energy recovery and optimising resource utilisation, hence minimising environmental impact. Third, categorisation allows for assessing the emissions, residues, and potential environmental risks associated with each WtE/WtF technology. A solid assessment of these facilitates in turn the selection of the most *environmentally sustainable* option, while ensuring compliance with the various environmental and safety regulations. Fourth, a clear classification and thus understanding of WtE/WtF technologies provides a solid *R&D framework* for scientists and engineers to focus on improving existing technologies or developing novel, innovative ones. Finally, categorisation assists stakeholders in conducting thorough cost-benefit analyses (considering, e.g., capital investment, operational expenses, revenue generation) to accurately assess the *economic viability* of a proposed technological solution.

Several ways of categorising waste recycling technologies in general and WtF to WtE technologies in particular have been proposed so far, based on various criteria. For example, one may consider the nature of the processes involved in plastics recycling as the sorting criterion. Physical processes (e.g., mechanical shredding, thermal melting, solvent dissolution) only change the physical characteristics of the plastic materials (e.g., size, shape, phase). Instead, chemical processes (i.e., chemical reactions) alter the chemical properties of the constituent polymers (e.g., chemical composition, molecular structure). Based on this criterion, the plastic recycling processes are divided into physical process like mechanical recycling and solvent-based purification, and chemical processes such as depolymerisation, thermolysis, and biodegradation[8].

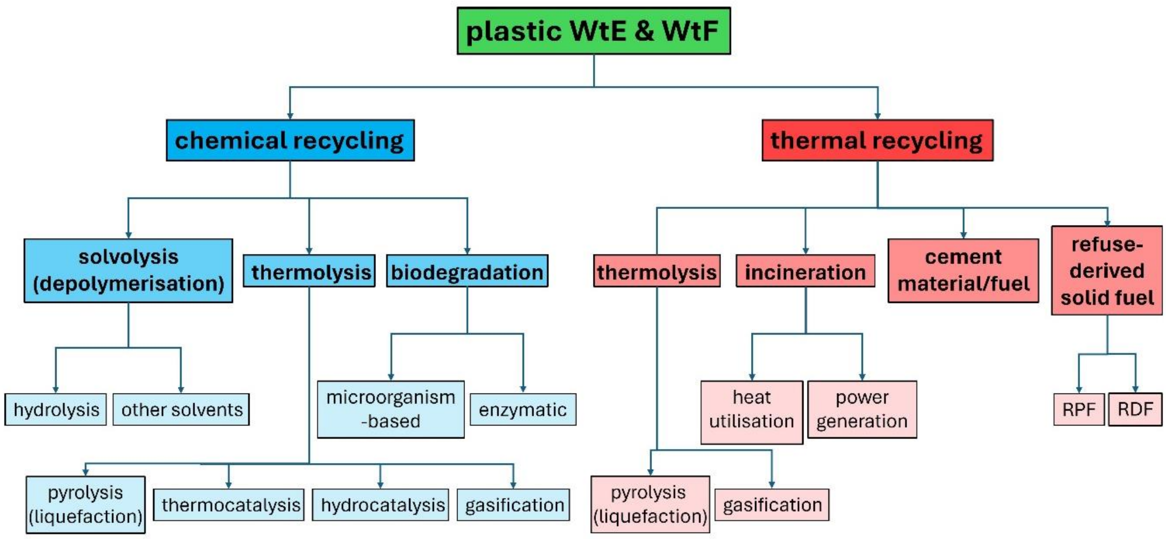

Figure 4. Categorization of plastic Waste to Energy and Waste to Fuel technologies based on the products (chemicals or energy) derived. RPF and RDF stand for Refuse Paper and Plastic Fuel and Refuse-Derived Fuel, respectively. Created utilizing information from references[7,8].

All existing plastic WtE and WtF technologies make use of one or several chemical reactions, therefore such a classification is not particularly helpful for the purpose of this document.

Alternatively, if we consider the *type of product* derived as the main criterion, plastic WtE and WtF strategies can be classified into two main categories (see **Figure 4**). *Chemical recycling* is a broad term referring to a family of technologies that achieve the breaking down of macromolecules to lower molecular weight fragments. We here use the term *thermal recycling* to describe technologies that are based on the thermal treatment (typically at high temperatures) of plastic waste with the main purpose of *energy recovery*. The analysis of the various WtE and WtF technologies provided in the following sections is based on the classification shown in **Figure 4**. It is worth noting that another important category often encountered when a product-based classification is conducted, material recycling[7], is not included here. This is because material recycling results in plastic products (i.e., whole items like bottles) or raw materials (i.e., the recycled constituent polymers); both product types do not fall within the range of energy or fuels and are therefore outside the scope of this document.

2.2 Chemical recycling technologies

Chemical recycling technologies can be divided into three types. *Solvolysis*, from the words solvent and lysis (to dissolve), refers to processes in which a chemical substance is used to break down macromolecules into smaller molecules. Instead of using solvents, the breaking down of a polymer chain into its constituent molecules can be achieved by exposing the polymer to high temperature; these types of thermal processes are described by the broad term *thermolysis*. Finally, *biodegradation* is a general term describing processes that exploit a series of biochemical reactions to fragment polymer chains.

2.2.1 Solvolytic or depolymerization technologies

Hydrolysis and other solvolysis processes

Concept. Depolymerization, also known as chemolysis (and, in some cases, monomerization), is the process by which a polymer chain is broken down into shorter molecular fragments. These may be either fractions of lower molecular weight than the one of the polymer (called oligomers) or monomer molecules (the building blocks of the polymers). This process, which is essentially the reverse of the polymerization reaction, can be achieved using solvents, chemical reactions, and/or heat. Depolymerization is mainly employed for obtaining monomers that can be then reused to yield polymers. Therefore, it cannot be considered a pure WtF process. However, we include it in this report because one may consider that monomer is essentially a chemical 'fuel' (in a looser use of the term) for producing new polymeric materials.

Process. Solvolytic processes, also known as chemical depolymerization methods (to distinguish them from thermolytic technologies that involve depolymerisation assisted by the high temperatures employed, see next subsection), involve breaking down polymers into smaller molecular units utilising specific solvents (**Figure 5**). The glycolysis of polyesters is achieved by means of a glycol-based solvent, usually ethylene glycol. It is often used for the chemical recycling of PET from bottles. The hydrolysis of polyamides makes use of water as the solvent that cleaves the amide bonds in the polymer, yielding amine and carboxylic acid monomers. It is employed for the chemical recycling of nylon-based materials, including textiles. The solvolysis of polyurethanes involves solvents with alcohol or other reactive groups, employed to break the urethane linkages in the chains. The reaction yields smaller units, including polyols and isocyanates, and it is used for the chemical recycling of polyurethane foams and elastomers[14].

Pros and Cons. The main advantage of depolymerization is that the monomers obtained from

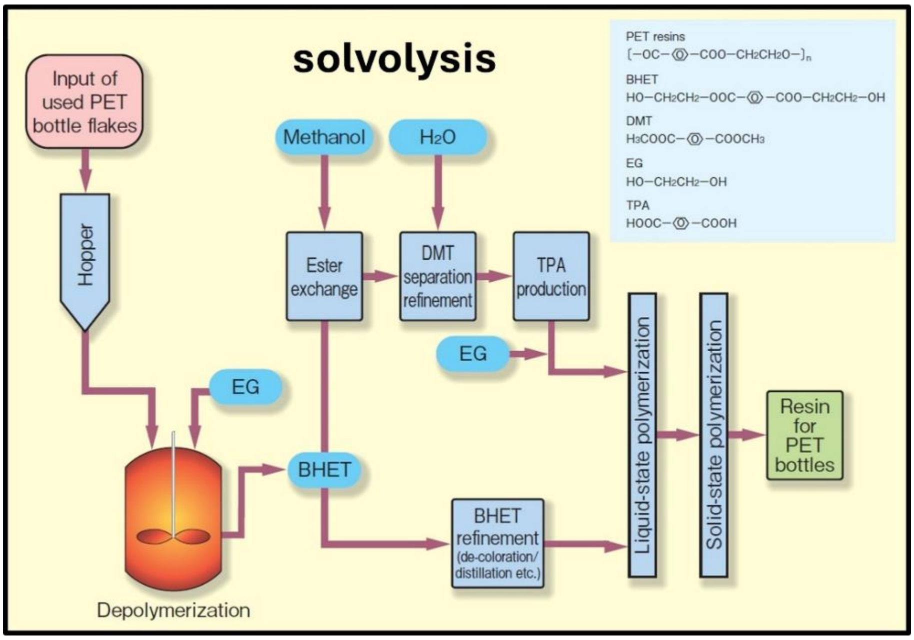

Figure 5. Schematic representation of the outline of the depolymerisation process of used polyethylene terephthalate. Adapted from reference[7].

this process have physical and chemical properties identical to those exhibited by 'virgin' monomers and, as a result, the polymers derived from both grades of building blocks are identical in quality. The main drawback of depolymerization is that it is only applicable to condensation polymers (i.e., polymers, the formation of which involves a condensation reaction that is, a small molecule is also produced as a byproduct) like PET and polyamides. Contrarily, it is unsuitable for breaking down most addition polymers (i.e., macromolecules that form by the simple linking of monomers without the co-generation of other products) that dominate the plastic waste stream, such as PE, PP, and PVC[10].

Feedstock. The feedstock used for depolymerization includes polyesters (e.g., PET, polybutylene terephthalate), polyamides (e.g., nylon-6, nylon-66), and polyurethanes[10].

Products. The most useful products of depolymerization are the monomers of the polymers decomposed. Most characteristic examples are ethylene glycol and terephthalic acid or dimethyl terephthalate (from polyesters), diamines and diacids or diols and diisocyanates (from polyamides), and polyols and isocyanates (from polyurethanes).

Technology Status. There are several industrial plants conducting degradation of PET, which mostly relies on methanolysis and glycolysis (employing methanol and glycol-based solvents, respectively) treatments. Hydrolysis may also be employed for breaking down PET, however processes based on it are less advanced, thus currently remaining mostly at the laboratory or pilot-plant scale. Degradation of polyurethanes is mostly carried our utilising glycolysis and hydrolysis methods, while the depolymerization of polyamides is mainly achieved by using hydrolytic treatments[10].

2.2.2 Thermolytic technologies

Pyrolysis or thermal liquefaction

Concept. In this process, also known as thermal cracking, plastic materials are heated in the *absence of oxygen* and are broken down into a number of basic hydrocarbons that form a gaseous phase. The resulting hydrocarbons can be either used directly as fuel, or can be separated into a range of products from heavy wax and oils to light oils and gas, by means of conventional refining

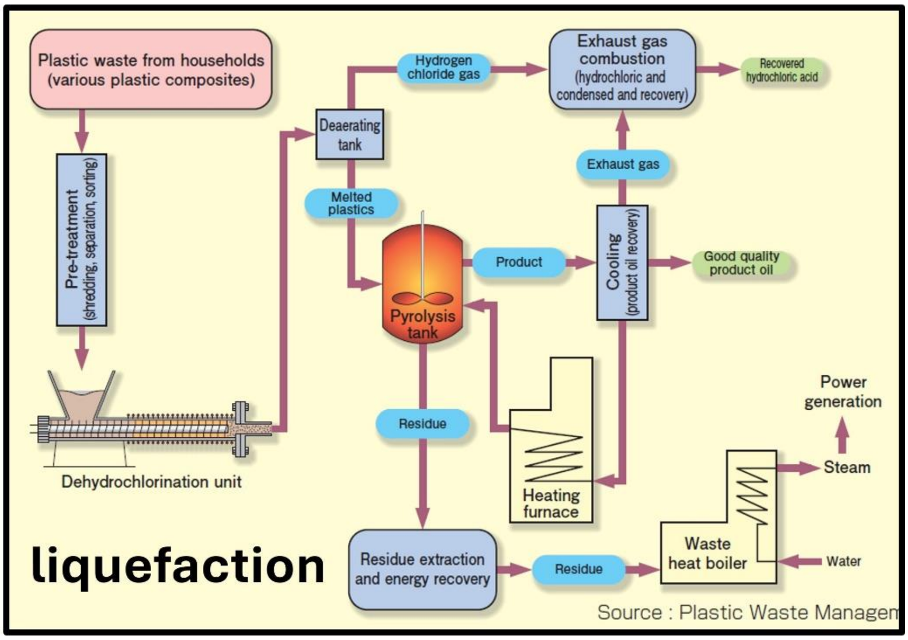

Figure 6. Schematic outline of the liquefaction process of household plastic waste. Adapted from reference[7].

technologies (e.g., distillation). To production can be shifted toward lighter or heavier products by adjusting the process time and temperature. Furthermore, heavier products may be reintroduced into the process for further decomposition into lighter products[10].

Process. A typical pyrolysis process (**Figure 6**)involves the preparation of feedstock, which are then fed into the pyrolysis reactor. There, the feedstock is subjected to high temperatures (commonly in the range of 400-800 ^{o}C); the absence of oxygen prevents combustion of the feedstock material. At these elevated temperatures, the organic materials making up the feedstock vaporise, and gaseous substances (e.g., volatile organic compounds, hydrocarbons, and other gases) are formed. The latter are then cooled down and condensation occurs, transforming the pyrolysis gases to liquid and solid products. The final step of the process typically involves collection and separation of the products.

Pros and Cons. A key advantage of pyrolysis is that it can be used to process contaminated and/or mixtures of polymers with other types of waste[10].

Feedstock. The plastic waste feedstock used for pyrolysis includes polyolefins (e.g., PE, PP), PMMA, as well as PS.

Products. The typical products of pyrolysis comprise pyrolysis oil (a mixture of hydrocarbons that can serve as fuel or feedstock for producing chemicals), synthetic gas (called *syngas*; typically consisting of H_2, CO, CO_2, CH_4, and N_2), and char (a carbon-rich solid residue that can be utilised in various industrial applications).

Technology Status. Traditionally, commercial plants using pyrolysis process charcoal, municipal solid waste, and biomass. Pyrolysis of mixed plastic waste has been mostly developing over the last two decades and it is only currently becoming a reality with a number of commercial plants operating currently, while more industrial-scale units are expected to be operational over the coming years[10].

Gasification

Concept. Gasification is a process that converts carbon-based raw materials into a gas mixture of simple components by exposing the carbonaceous materials to high temperatures (typically

>700 ^{o}C) inside a chamber, in which the *amount of oxygen and/or steam present is controlled*. The produced syngas (or *producer gas*) may then be used to produce energy directly (e.g., via combustion), energy carriers (e.g., H_2), and a plethora of chemicals that can be used as fuels (e.g., hydrocarbons), building blocks for synthesising new polymers (various monomers), or in other chemical reactions and applications (e.g., fertilizers)[10,11,15].

Process. The gasification process begins by first preparing the carbon-rich waste materials and then introducing them into the gasification reactor. Inside the latter, the feedstock is heated to very high temperatures (typically 700-1,500 ^{o}C) in an environment where the supply of oxygen or air is limited and precisely controlled. The restricted amount of O_2 allows for only partial combustion of the waste material, which produces CO_2 and H_2O vapour. This partial burning, combined with thermal decomposition of the feedstock leads to the formation of syngas, which is then processes to remove impurities (e.g., tar, sulphur, and particulates). The purified syngas can be employed for generating electrical power, fuel synthesis, or synthesis of other chemicals.

Pros and Cons. A key advantage of gasification, for example when compared to other commonly used plastic waste valorisation routes such as pyrolysis, is its greater flexibility to jointly exploit plastics of different composition or wate mixtures of plastics and other feedstocks. Moreover, the composition and, as a result, the applications of the produced gas depends on the gasifying agent utilised. For example, air gasification of plastic waste yields a syngas with an average heating value of 6-8 MJ/m^3, useful for energy production, whereas steam gasification enables the production of N_2-free syngas with a heating value higher than 15 MJ/m^3, useful for synthesis applications[15]. The main challenge associated with the gasification of waste plastics is the requirement, especially for the production of chemical feedstock, of a very efficient gas purification system able to remove the high tar content in the gas product[15]. Furthermore, gasification typically necessitates pre-treatment to reduce the amount of moisture and increase the calorific value of the feedstock[10].

Feedstock. The feedstock used for gasification includes all plastics[10].

Products. As already mentioned, the primary product of gasification is syngas. However, this process can also yield other valuable byproducts, depending on the properties of the feedstock as well as the operating conditions. These include tar that, although considered an impurity, can be

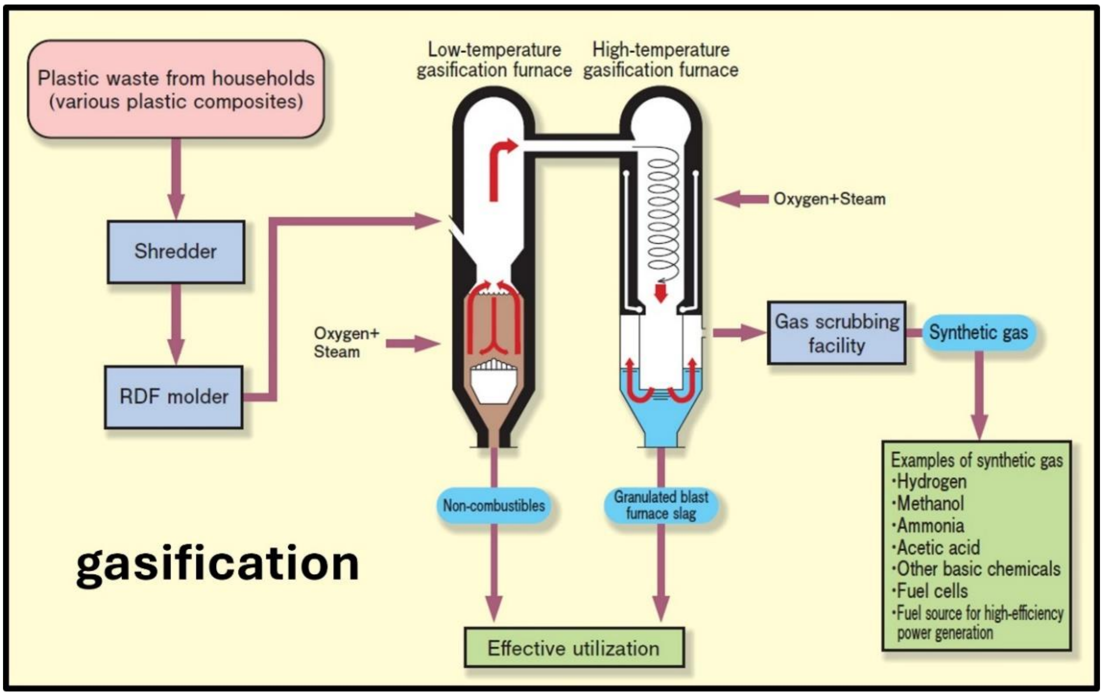

Figure 6. Graphical representation of the outline of the gasification process of household plastic waste. Adapted from reference[7].

utilised (e.g., as fuel or a source of chemicals), char that can be used as a solid fuel or soil amendment, and ash which can be used in construction materials. Besides these byproducts, the large amount of heat produced by the exothermic gasification process, as well as the water vapour produced may be used for heating or electricity generation.

Technology Status. Gasification is usually carried out in larger process units designed to achieve economies of scale. Hence, gasification plants are typically built at a large scale than, e.g., pyrolysis plants[10]. The gasification of municipal solid waste has shown increased popularity due to the increasing technical, economic, and environmental concerns associated with waste incineration[16]. For example, as of 2019, 33 gasification plants processing chiefly carbon-based fuels like coal and petroleum, with smaller amount of waste feedstock, were running in the USA. Small-scale municipal solid waste gasifiers are in increasing demand and compact gasification units, thanks to their flexibility, could be integrated within existing industrial and thermoelectric plants[16].

Hydrothermal Liquefaction

Concept. In hydrothermal liquefaction, also called hydrous pyrolysis, a compound is decomposed by water molecules that are in a super-critical condition (i.e., at a temperature and pressure above its critical point), in a reaction that is called *hydrolysis*. Typically, the temperature of the process is in the range 160-240 ^{o}C and a corresponding pressure to keep the water supercritical[10].

Process. The process of hydrothermal liquefaction begins by collecting plastic waste, which may include various types of common polymers. The waste feedstock is mixed with water to create a slurry, which is then pressurised (typically in the range of 10-25 MPa); high pressure is critical for keeping the water in its liquid state at the high temperatures employed. The temperature is elevated, commonly within the range of 250-400 ^{o}C. The combination of high pressure and temperature, in the presence of water, induces thermochemical reactions; the macromolecules undergo thermal decomposition and liquefy. The resulting hydrocarbon oil is separated from the aqueous phase and may undergo further refining or upgrading processes.

Pros and Cons. A key advantage of hydrothermal liquefaction is that it is effective in processing plastic waste of various types, including mixed or contaminated plastics that are challenging to recycle through other common methods. However, plastic waste often contains contaminants and additives that are difficult to eliminate and may require additional processing steps to prevent them from being present in the final oil products. Other drawbacks of hydrothermal liquefaction are its energy intensive nature, the challenges associated with the scaling up of the process, as well as its debated economic viability.

Feedstock. The feedstock used for hydrothermal treatment includes plastic packaging waste (e.g., PET), polycarbonate, styrene-butadiene copolymers, polylactic acid, polyamides (e.g., nylon-6, nylon-66), carbon fibre-reinforced plastics, as well as printed circuit boards[10].

Products. The main product derived from hydrothermal treatment is synthetic crude oil, which can be further separated, purified, and upgraded utilising standard refinery processes[10].

Technology Status. Hydrothermal treatment is a technology that is still developing, with some commercial operations are in the planning stage (see **Chapter 3**)[10].

2.2.3 Biodegradation technologies

Microorganism-based decomposition

Concept. The common basis of the various microorganism-based biodegradation technologies is the utilisation of *living organisms*, especially bacteria and fungi, which produce enzymes (protein molecules that facilitate specific chemical reactions) that can break down the macromolecular structure of various plastics. The latter include materials made from both natural and fossil-based synthetic polymers[17]. Microorganisms employ various mechanisms to degrade these complex macromolecules. These mechanisms include the direct use of plastic fragments as a nutritional source or the indirect (catalytic) action of various microbial enzymes. Compared to the related concept of enzymatic decomposition (discussed in the next subsection), microorganism-based decomposition encompasses the overall action of the entire microorganisms, including their diverse enzymatic activities. For polymer biodegradation, examples of widely used bacterial and fungal strains are the *Pseudomonas fluorescens*, *P. aeruginosa*, and *Penicillium simplicissimum*[17].

Process. Bacteria and fungi are capable of degrading both biobased and fossil-based polymers into CO_2 and H_2O via various metabolic and enzymatic mechanisms. The nature and catalytic activity of enzymes are dependent on the microbial species and vary even within the strains. As a result, different enzymes have been shown to degrade various polymers. For instance, *Bacillus* spp. and *Brevibacillus* spp. produce proteases that participate in the degradation of various polymers. Fungi, which biologically degrade lignin, often contain laccases to catalyse aromatic and non-aromatic compounds via oxidation.

The initial step in the biodegradation of plastics is the colonisation of the plastic surface by microorganisms, which cause a reduction in size of the constituent polymers. The resulting monomers can then enter the microbial cells, where they are further processed by enzymatic degradation; eventually, the monomers serve as carbon source for growth. Upon enzymatic degradation, mineralisation of the monomers occurs and various end-products are derived[18]. Under aerobic conditions, oxygen serves as an electron acceptor by the bacteria and CO_2 and H_2O are derived as main end-products, alongside other metabolic products. Under anaerobic conditions, the macromolecules are broken down in the absence of O_2 by the microbes. Anaerobic bacteria use sulfate, nitrate, iron, carbon dioxide, and manganese as electron acceptors and the final products are CH_4, CO_2, H_2 and other residues[17]. Besides the elimination of plastic waste, methane, one of the main gases produced, can be used as a biofuel and for manufacturing other useful chemicals.

Pros and cons. Microbial biodegradation exploits the natural metabolic activities of microorganisms, which are part of natural ecosystems and play an important role in the carbon cycle. In addition, such technologies can potentially target a broad range of plastics, including complex ones. Furthermore, they are environmentally friendly, since thy mostly take place under ambient conditions without necessitating high temperatures or elaborate equipment. Another advantage of biodegradation is that it can contribute to soil improvement. On the contrary, biodegradation processes are generally slow, limiting their suitability for quick waste management. Additional limitations include the variable efficiency of biodegradation (depending, for instance, on environmental conditions and microbial activity) and the variability of the end products (some processes may yield residues or byproducts).

Feedstock. Both biodegradable and non-biodegradable plastics that are based on polymers such as polyhydroxyalkanoate, polylactic acid, PET, polyhydroxy butyrate, PVC, polycaprolactone, and polybutylene succinate are reported interact with various microbes and their enzymes[17]**.**

Products. The metabolism of polymer chains by various microbes results in the formation of various metabolic byproducts, such as organic acids, alcohols, and other smaller molecules that can be useful in the chemical industry. In addition, gases (e.g., CO_2 and CH_4) are frequently produced as byproducts of microbial activity during plastic decomposition; these may serve as biofuels. Finally, the microbial biomass produced as the microorganisms use the carbon and energy derived from plastic degradation, can be considered another product of the plastic decomposition process.

Technology status. The microbe-based biodegradation is a well-established process, which takes place naturally in various environments as well as in composting processes. Regarding plastics in particular, the study of microorganisms with significant plastic-degrading capabilities is an active field of research. However, its implementation in specific plastic waste management systems is, to a large extent, still being optimised.

Enzymatic decomposition

Concept. Enzymatic decomposition involves the utilisation of *specific enzymes* to catalyse the breaking down of polymers into simpler molecules. It specifically focuses on the role of enzymes as biological catalysts in the decomposition process. In practice, such enzymes are often isolated by the microorganisms that produce them. These features differentiate enzymatic degradation from the similar concept of microbe-based decomposition that refers to the *collective* action of the microorganisms to degrade plastic, as described earlier.

Process. Several enzymes have been isolated from various microorganisms such as bacteria, fungi, algae, and actinomycetes, which are known to cause degradation of many polymers encountered in plastic materials. All enzymes that are known to decompose such polymers are hydrolases. Enzymes of this category participate to a catalytic reaction that causes the breakdown of the chemical bonds of the polymer substrate in the presence of water. Some examples of common enzymes that are associated with plastic degradation are cutinase, lipase and PETase. Intense research and development is carried out for extracting these enzymes and modifying them with the purpose of increasing their enzymatic activity[18].

Pros and cons. On the one hand, enzymatic biodegradation takes advantage of the targeted specificity of enzymes, which can be engineered to target specific polymers, enhancing the specificity of the degradation process. Furthermore, compared to microbial processes, enzymatic reactions can often proceed faster. Finally, enzymatic biodegradation can take place under controlled conditions, enabling optimisation and scalability. On the other hand, enzymes can be expensive to produce, which may lead to an increase of the overall cost of the process. Moreover, the development and optimisation of enzymes can be quite demanding, as it may require advanced biotechnological strategies. Finally, scaling up enzymatic processes for industrial implementation is challenging, both from a technical and an economic perspective.

Feedstock. Numerous types of polymers including PE, PET, polylactic acid, polybutylene succinate, and polyurethanes have been shown to experience slow degradation in the presence of cutinases, lipases, and esterases[18].

Products. The breaking down of polymer chains due to the action of enzymes yields monomers and oligomers, which may be useful chemical feedstock to produce new polymers. Moreover, since enzymes are often specific to certain types of chemical bonds, the polymer degradation process can result in the formation of specific molecules (based on the chemical structure of the original polymer) that can be useful in the chemical industry. Finally, as in the case of microbial decomposition described earlier, enzymatic degradation yields microbial biomass.

Technology status. Enzymatic biodegradation is an emerging sector that receives increased attention from both researchers and industrial players. Many of the involved technologies have shown promising results in the laboratory scale and efforts are underway to scale them up for industrial applications. Interestingly, some of these technologies are currently transitioning from the research phase to commercialisation, with companies exploring ways to integrate enzymatic processes into plastic recycling systems (see also **Section 3.1**).

2.3 Thermal recycling technologies

Thermal recycling technologies can be classified into four main types. *Thermolysis*, as already mentioned, breaks down macromolecules into simpler molecules via the application of thermal energy. *Incineration*, the controlled combustion of waste at high temperature, is the most widely employed technology of thermal conversion. *Refuse-derived solid fuel*, also known as 'engineered fuel', is a solid fuel typically derived from non-recycled waste materials that is utilised in power generation and heavy industry applications. A noteworthy example of the latter is cement production, in which Refuse-Derived Fuel provides a complementary raw *cement material/fuel*.

2.3.1 Thermolysis

The various thermolysis technologies have been analysed in **subsection 2.2.2**, in the frame of chemical recycling technologies that exploit high-temperature processes to break down complex polymers into simpler molecules that are then used as monomers or other chemicals. Besides feedstock production, some thermolytic technologies can be used to produce/recover energy. For instance, pyrolysis can transform (non-recycled) plastics into a synthetic type of crude oil that can be further refined into various fuels such as diesel, gasoline, or heating oil. Another example is gasification that can turn plastics into syngas, which in turn can either be utilised to directly generate electrical power or be converted into fuel[12].

2.3.2 Incineration

Incineration for heat utilisation or power generation

Concept. Incineration is a method for treating waste, including plastics, which involves the *combustion* of organic substances (see **Figure 7**). Combustion refers to a high-temperature exothermic redox chemical reaction between a fuel (the reductant) and oxidant (often atmospheric O_2) that produces oxidised products, in a mixture that is called smoke. The purpose of incineration is to reduce the waste volume, decrease or eliminate the presence of hazardous materials, and generate energy of various forms.

Process. In the initial incineration stage, plastic waste is sorted to remove non-combustible materials and hazardous waste that may interfere with the process. The sorted feedstock is introduced in the incinerator, where combustion takes place at very high temperatures (typically 800-1,200 ^{o}C). The generated heat is utilised to produce steam, which in turn is either used directly, or utilised to generate electricity through turbines. Control technologies are employed to minimise the release of pollutants to the atmosphere (e.g., particulates, nitrogen oxides NO_x, SO_2, and dioxins), while ash and other residues are collected and managed.

Pros and Cons. A key advantage of incineration is that it can handle unprocessed or unsorted plastic waste, such as the one contained in municipal solid waste. Besides the energy recovered, the waste volume is reduced by about 90%, offering an alternative to landfilling[16].

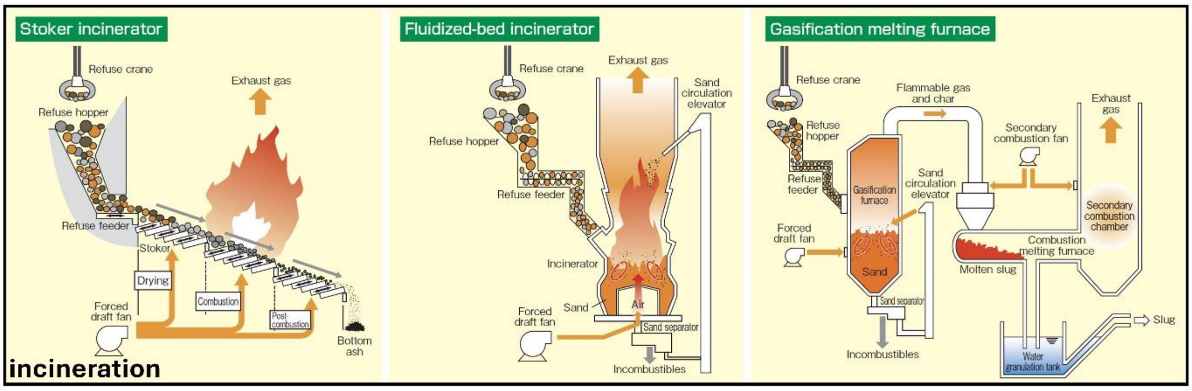

Figure 7. Schemes of typical incineration systems currently in use. Adapted from reference[7].

Incineration is accompanied by the formation of gaseous pollutants such as sulphur oxides (SO_x), carbon oxides (CO_x), and NO_x as well as polyaromatic hydrocarbons and heavy metals. These substances are dangerous and must be treated before being released into the atmosphere[19]. Additionally, some incinerators necessitate the pre-drying of waste if it contains a high concentration of moisture. Finally, the leftover ash may contain inorganic pollutants that can be released into the environment, hence requiring proper disposal[16].

Feedstock. The feedstock used for incineration can be of various sources, including packaging materials, single-use plastic items, as well as non-recyclable plastics. However, to ensure efficient burning, an appropriate segregation of waste is necessary.

Products. As already mentioned, the primary product of incineration is thermal energy, which can be used for heating applications directly, or for producing steam. The steam can be used to produce electricity. Ash and other residues like heavy metals, non-combustible materials, and other pollutants are typically unwanted products of incineration.

Technology Status. Incineration is a well-established and mature, as a result, a widely implemented technology for treating plastic waste (see **Chapter 3**). Ongoing advancements concentrate on enhancing emission control technologies, improving energy efficiency, and addressing associated environmental concerns.

2.3.3 Cement material/fuel

Concept. Any incineration system produces heat and exhaust gas, which can be utilised, directly or indirectly, as a new energy source. Plastic refuse, owing to its high calorific value and good combustibility, may additionally serve as a partial replacement of traditional fossil fuels used in the energy-intensive cement industry.

Process. Typically, after undergoing a few sorting and processing steps (e.g., removing of non-combustible materials, shredding into smaller pieces), plastic waste enters a *cement kiln* alongside traditional fuels (e.g., coal, natural gas). The plastic waste undergoes combustion and consequently contributes energy to the high-temperature processes taking place within the kiln[7,20].

Pros and Cons. The utilisation of plastic waste in cement kilns is advantageous, because the waste feedstock serves as an alternative fuel source that (partly) replaces traditional fossil fuels. At the same time, it provides a means of processing hard to recycle or non-recyclable plastics. On the other hand, drawbacks of this technology include concerns about pollutant emissions, production of potentially harmful byproducts (e.g., from incomplete combustion), and the potential negative impact on the quality of the produced cement.

Feedstock. A broad range of plastics can be introduced in cement kilns (e.g., LDPE, PP, PS, PET, plastics from electronic waste, automotive plastics, textiles). Nevertheless, the type of accepted feedstock may vary depending on the capabilities of the cement plant and the desired energy recovery outcomes. Furthermore, a consistent and controlled feedstock is desirable to optimise combustion.

Products. The primary products of this waste processing technology include energy (in the form of heat and electricity), cement clinker (a nodular substance formed in the high-temperature process taking place in the cement kiln), and cement. As with any combustion process, other residues like ash are also generated as byproducts.

Technology Status. The co-processing of plastic waste in cement kilns is a well-established and broadly implemented technology for converting plastic waste to energy (see **Chapter 3**). Despite this, ongoing effort is put for optimising the combustion process and ensuring environmental sustainability within the cement industry.

2.3.4 Refuse-derived solid fuel

Concept. Refused-Derived solid Fuel (RDF) is a type of fuel produced by processing various types of non-hazardous single or mixed waste streams, such as municipal solid waste, construction and demolition waste, and industrial waste. Various plastics are an abundant component of RDF. Compared to the raw waste material, RDF is designed to be a more uniform and energy-dense fuel.

Process. The process of generating RDF from plastic waste involves mechanically sorting and shredding mixed solid waste, including plastic components, to create a homogeneous fuel product. The resulting RDF, typically containing plastics with other combustible materials, is then processed, and compacted into a solid fuel suitable for use in waste-to-energy facilities or industrial boilers.

Pros and Cons. The properties of RDF make it suitable for utilisation in various industrial processes, such as in cement production (discussed above) and power generation. However, RDF still exhibits high heterogeneity, low friability, and contains significant amounts of moisture, ash, and chlorine. As a result, deriving energy from RDF may be accompanied by emissions (e.g., dioxins, hydrochloric acid) that are harmful to humans and can damage the processing equipment. For these reasons, regulations currently in place set high quality standards for RDF to be used for energy production[21].

Feedstock. RDF is typically produced from municipal solid waste, which may contain a plethora of plastics. These include, for instance, polymers in the form of packaging materials and films (composed of, e.g., PE, PP, PET, PS).

Products. As mentioned above, RDF is a processed and standardized fuel derived from the mechanical sorting and processing of, typically, municipal solid waste, including a mixture of organic and combustible materials.

Technology Status. The technology for generating RDF is well-established, with widespread application in waste management systems globally. Ongoing developments in sorting technologies, quality control, and process efficiency contribute to the continuous optimization of RDF production.

2.4 Other technologies not suitable for plastic waste

Landfilling with Energy Recovery

Landfill with energy recovery, also known as landfill gas to energy involves the extraction and use of gases produced during the natural decomposition of carbon-based waste in landfills. These gases comprise mostly CH_4, along with CO_2 and smaller amounts of other gases. Instead of releasing these gases into the atmosphere, they are captured, processed, and utilised as an energy resource. This can be done, e.g., by using the landfill gas to drive electricity-generating turbines. This technology is mostly suitable for processing food waste and other biodegradable materials. The decomposition of most plastics in the anaerobic conditions of landfills is slow and hence the energy recovery limited, rendering plastics unsuitable raw material for this technology[22].

Anaerobic digestion

Anaerobic Digestion is a biological process in which microorganisms break down organic compounds in the absence of oxygen, producing biogas as a byproduct. It is most often employed for decomposing food waste, agricultural residues, and sewage sludge. Plastic waste is not typically suitable for anaerobic digestion[22].

3. COMMERCIAL STATE OF THE ART

In this chapter, we first describe a number of important companies, whose all or part of operations are associated with plastic waste to energy and waste to fuel activities (**Section 3.1**). It is worth noting that this list (summarised in **Table 1**) is neither exhaustive nor includes only large companies. Instead, we attempted to capture representative companies that exploit a large portion of the technologies analysed in **Chapter 2**. In **Section 3.2**, the current commercial state of these companies is discussed, along with significant relevant investments and key partnerships, over the recent years.

3.1 Companies operating in the WtE/WtF sectors

Mura Technology Limited is a UK-based company whose mission is to globally scale a technology called HydroPRS™ that can recycle a broad range of waste plastics (including flexible and multi-layered materials), with a low carbon footprint. This is a protected and validated process with more than 5 years of R&D at pilot scale and a global pipeline that is expected to reach a recycling capacity of 1.5 Mt in operation or development by 2032. It is worth noting that Mura holds the exclusive licence to the Cat-HTR™ technology of Licella Holdings Ltd (an Australian biotechnology company who is the largest shareholder of Mura) for post-consumer plastic processing outside of Australia and New Zealand[23]. HydroPRS™ relies on the utilisation of *supercritical water* to break the carbon-carbon bonds in waste plastics and yield stable hydrocarbon products. Besides making this technology inherently scalable, the use of supercritical water offers additional significant advantages. These include the processing of a wide scope of plastics (due to its insensitivity to organic contaminants) and a high product yield (due to the production of neither char nor unwanted byproducts, and control of the reaction conditions). Mura's business model includes both production from their own-built sites in the UK, USA and Europe, as well as the offering of licence opportunities via their Licensing and Engineering Partner, KBR[24].

Itero Technologies Limited is a UK-based chemical recycling company that employs a proprietary *pyrolysis* technology to convert hard-to-recycle waste plastic into a chemical feedstock, which can be used for making brand new circular plastic products. Itero's end-to-end plant comprises their proprietary pyrolysis and liquid hydrocarbon recovery technologies, integrated with low-risk industry standard components. After screening the incoming feedstock, their module converts it to smaller hydrocarbons via thermal cracking, with a conversion capacity of 27 kt/year. The hydrocarbon product fractions are separated by tunable condensers, while uncondensed pyrolysis gases are cleaned and re-introduced to the system to generate heat, making the process self-sustained. The four main products derived are pyrolysis oils (a circular substitute of naphtha), recycled waxes (hydrocarbon compounds with various industrial and consumer applications), pyrolysis gas (used to thermally sustain the pyrolysis process, as mentioned), and char (a carbon-rich residue with element recovery potential)[25].

BlueAlp is a Netherlands-based company that utilises a patent-protected *slow cracking* technology that cracks plastic feedstock in an oxygen-free heating process, to convert it to valuable feedstock. BlueAlp's technology upcycles any plastic waste into high-quality feedstock (in part due to a combination of patented features to remove contaminants) using comparatively low energy and has a number of significant advantages. These include the capability to recycle waste comprising a broad mix of plastic feedstock, resulting in higher feedstock availability and lower cost. Furthermore, the fact that no limitations exist in the utilised heat transformers enables scaling up a single reactor train to 50 kt, resulting in both capital and operating expenses reductions. Moreover, the continuous liquid phase pyrolysis process results in high control and an efficient operation. Finally, additional advantages include an efficient energy balance (due to the low heat flux), the fact that no catalysts are required (which are often expensive), and very high oil and gas safety standards (allowing for the optimal integration of the site within a chemical complex).

Company	HQ	Est.	Technology	Products
Mura Technology Ltd	London (UK)	2016	hydrothermal liquefaction	-own sites producing hydrocarbons -technology licensing
Itero Technologies Ltd	London (UK)	2010	pyrolysis	-pyrolysis oil -recycled wax -pyrolysis gas (reused) -char
BlueAlp	Eindhoven (Netherlands)	2014	pyrolysis	-technology licenses -complete plant development
Plastic Energy Ltd	London (UK)	2011	pyrolysis	- patented TAC™ process - TACOIL™ (recycled oil)
Veolia Sheffield (started as Associated Heat Services, AHS)	Sheffield (UK)	1966 (AHS)	incineration	-hot water -electricity
Carbios SA	Clermont-Ferrand (France)	2011	enzymatic biodegradation	-enzymatic recycling & biodegradation technology -enzymes
Agilyx Corporation	Portsmouth, NH (USA)	2004	pyrolysis	-conversion technology licensing -specialised equipment sale
Covanta Holding Corporation	Morristown, NJ (USA)	1939 (Ogden Corp.)	incineration	-electricity -steam -recycled metals
Geocycle (Holcim Ltd)	Holderbank (Switzerland)	2007	cement kiln	-various technical services (e.g., risk assessment, on-site handling, packaging)
SynPet Technologies	Brussels (Belgium)	2014	combination	-proprietary TCP™ process for renewable crude oil & natural gas, liquid fertilisers, biochar

Table 1. Summary of key companies operating in the plastic Waste to Energy and Waste to Fuel sectors.

BlueAlp offers either licenses for their technology, with the customer implementing the design with their own preferred EPCM partners, or a complete plant in which engineering, procurement and fabrication is overseen by BlueAlp[26].

Plastic Energy Limited is a company headquartered in UK that is active in the conversion of end-of-life plastics into feedstock, via their patented technology called the TAC™ process. The latter begins by heating plastics to melt them before they are fed to a reactor. The melt is further heated in the reactor, in the *absence of oxygen*, and transforms from liquid to gas, with a small amount of char produced as well. This is followed by condensation of the produced vapours, which are also further refined through a series of separation and filtration steps. The final product, apart from synthetic gas that is utilised for heating the reactors, is a recycled oil called TACOIL™. This synthetic output is stored for sale to Plastic Energy's petrochemical partners. TACOIL™ has been used to make more than 10 commercial products in the European market, including Unilever's Magnum ice cream tubs, Mondelez's Philadelphia cream cheese packaging, and Kraft Heinz's 'Heinz Beanz' snap pots. Plastic Energy offers a complete licensing package with end-to-end support from an initial feasibility assessment through to operational and post-production support. In addition to their own facilities, Plastic Energy has an extensive portfolio of industry partnerships, which is briefly discussed in **Subsection 3.2**[27].

Veolia Sheffield, part of Veolia Environment SA, operates an energy recovery facility that converts rubbish (including plastic waste) into heat for the Sheffield District Energy network, and electricity for the UK National Grid. The whole process starts with the collection of garbage from local households, authority services, and businesses and storage into the bunker of the facility. The waste material is then introduced in a hopper by an overhead crane at a rate of 28 t/h. The hopper next feeds the waste into a single *incineration* unit, in which waste is combusted at temperatures higher than 850 ^{o}C. Superheated steam is generated in a boiler above the incinerator and is employed to drive a turbine generating electricity for the National Grid and produce hot water for the District Energy network. Additional processes are used to remove (and later dispose) particulates from the cooled flue gases, reduce emissions of NO_x, and capture other pollutant, so that only cleaned gases are released into the environment. Ash produced during the incineration is taken to be recycled into aggregate for the construction industry, while metal is recycled by a local company[28].

Carbios SA is a French biotechnology company that designs and develops enzymatic processes to address the issue of the end-of-life of plastics and textiles. Since its founding in 2011 by Truffle Capital, Carbios has developed two industrial processes for the biodegradation and recycling of polymers. Carbios' *enzymatic recycling* processes takes advantage of an enzyme capable of specifically depolymerizing PET. The resulting monomers undergo purification so that they can be re-polymerized into a PET of a quality equivalent to the virgin material. Carbios' technology enables the recycling of all types of used PET-based products, including waste that cannot be recovered using conventional recycling technologies. Carbios' enzymatic biodegradation process makes polylactic acid, a bioplastic with limited compostability, fully compostable even at room temperature. This is achieved thanks to CARBIOS Active, an enzyme developed by Carbiolice, a Carbios Group company. CARBIOS active directly introduced during the manufacturing of polylactic acid products, without necessitating any changes to production lines. The enzyme remains inactive throughout the useful life of the product, with no impact on its mechanical properties. The enzyme is activated only under composting conditions (e.g., specific temperature, humidity, pH), driving the complete disintegration of the material in an environmentally friendly manner. Carbios' business model relies on the industrialization and commercialization of its products and/or enzymes, technologies, and bioprocesses via license concessions directly or through joint ventures with major relevant industries[29].

Agilyx Corporation, part of the Agilyx Group, is a USA-based recycling company that utilises *pyrolysis* to convert all types of plastic waste plastic into their original building blocks for reuse. The company offers an end-to-end, integrated solution for plastic waste recycling, including both a chemical recycling technology as well as feedstock processing expertise. Agilyx's state of the art technology covers both stages of waste to feedstock (i.e., sourcing of the right amount of the appropriate quality of plastic at the right time while minimising cost) and feedstock to product (i.e., efficient conversion of waste to purified raw material). This technology, secured by 20 patents, is the result of about 20 years of experience in the chemical recycling industry and enables the conversion of hard-to-recycle plastics into valuable, low-carbon products. The patented reactor design allows for handling not just mixed waste plastic, but also specific streams like PS or PMMA. Advantageous features of Agilyx's technology include the employment of a catalyst-free system (which makes the processing of contaminated waste possible), the fact that it is a robust process (allowing for processing a wide range of plastic feedstocks and blends), and a reduced carbon footprint (due to the use of renewable energy sources). The business model of the company is based on the licensing of the company's conversion technology as well as the sales of specialised core equipment[30].

Covanta Holding Corporation, based in New Jersey, USA, operates WtE facilities that are designed to convert waste remaining after recycling processes into electricity for homes and businesses use, as well as steam for export to industries. Covanta's process starts with first removing unacceptable materials from the waste stream, which are sent for other types of recycling or proper disposal. The remaining waste is then thoroughly mixed, before being directed to the *combustion* chambers. There, waste is burnt at temperatures of about 1100 °C, in a self-sustaining process. As waste undergoes combustion, the produced heat converts water into steam. This steam drives a turbine-driven generator to produce electricity, or it can be used directly for heating or industrial processes. The generated electrical power is exported to local utilities, for utilisation in homes and businesses. Each ton of waste can yield 550 to 700 kWh of electricity. Steam from the process is condensed into water and introduced back to the boiler tubes, making it an efficient close-looped system. Remaining ash is beneficially reduced or landfilled as non-hazardous waste, while various metals are recovered. All produced gases are collected, filtered, and cleaned to minimize environmental impact. On a yearly basis, Covanta's facilities continuously power 1 million homes and recycle 600 kt of metal, while reducing greenhouse gas emissions by 21 Mt[31].

Geocyle, was founded in 2007 as the dedicated identity for branding waste management solutions in the Holcim Group, with the aim to unite all activities related to waste management solutions under a single and clearly positioned brand. Geocycle offers sustainable solutions to municipalities and industries for transforming waste into resources. This is achieved by both recycling and by valorising non-recyclable materials. Geocycle's process involves a pre-processing and a co-processing technology. The former refers to the conversion of a wide range of waste materials into a homogeneous mix of defined characteristics, which complies with the technical specifications of cement production and is thus suitable for *co-processing in cement kilns*. During co-processing, waste is exposed to high temperatures (more than 1100 °C) for long residence times, with the mineral part of the waste replacing primary mineral materials (e.g., limestone, clay or iron) and the combustible part yielding the energy required for producing clinker. Effectively, all the waste input is recycled and recovered without producing any residue. In addition, co-processing utilizes already existing cement plants with only moderate additional investments needed for waste handling, hence resulting in saving of public funds on waste management infrastructure. Geocycle provides several tailored services, such as risk assessment, on-site handling, packaging, labelling, and other solutions depending on the particular needs[32].

SynPet Technologies is a chemical recycling company offering waste management services that employ a proprietary Thermal Conversion Process (TCP™) to convert organic and petroleum-based hydrocarbons into valuable outcomes such as synthetic oil, renewable natural gas, and fertilisers, via a cost-effective technology. The TCP™ comprises three stages, in which different waste treatment technologies serve a single purpose. Organic and inorganic substances are treated with water under constant heat and pressure, resulting, via depolymerisation, in smaller organic substances which are then transferred to the next step. In the second step, carbon-based molecules are broken apart thanks to the water gas shift reaction, in which hydrogen and hydroxide attach to target carbon atoms. This allows all contaminants to be detached from the carbon-containing molecules. A secondary chemical reaction, decarboxylation, removes then all oxygen molecules from the hydrocarbons, producing pure long hydrocarbon chains. The final step involves the increase of temperature to above 450 °C, which induces thermal cracking that breaks chains of long-chain hydrocarbons into smaller fragments, resulting in high-quality end products. This technology can recycle wastes that cannot be recycled with other common methods, such as pyrolysis or gasification, and does not require the costly pretreatment of the waste (e.g., cleaning, separation, or drying). Feedstocks include a plethora of used polymers, including LDPE, PP, PS, PVC, other packaging waste, automotive shredder residue, medical waste, refinery waste, and hazardous waste[33].

3.2 Current company status, partnerships, and investments

Mura Technology. The first HydroPRS™ site of Mura, called ReNew ELP, is currently under development in Teesside, Northeast England. Commercial recycling operations, set to begin in 2024, are expected to offer to the market 20 kt of recycled, liquid hydrocarbons per year. Mura further plans to expand the site to over three times its initial size. The target feedstock is post-consumer, mixed plastic waste comprising flexible films, pots, tubs, trays, and other items. Innovate UK, the innovation agency of UK, granted the ReNew ELP project £4.42 million (approximately €5.19 million) in October 2021[24].

Itero Technologies. At their West London Pilot Plant, located near Heathrow, UK, Itero carries out feasibility testing for feedstocks of varying polymer and contaminant composition, to demonstrate the circular potential for a range of materials supplied by their industry partners. Itero's tested processes will be further expanded at an industrial-scale demonstration facility at the Brightlands Chemelot Campus, Netherlands, which is expected to start commissioning in the second half of 2025[25].

The Netherland's Enterprise Agency, Rijksdienst voor Ondernemend Nederland, awarded Itero a k€240 grant in October 2022, to be employed towards the demonstration plant of Itero's recycling process that can manage plastic waste streams otherwise destined for landfill or incineration. Furthermore, in July 2022, Itero received €5 million from the Infinity Recycling's Circular Plastics Fund, intended to support the design and construction of their demonstration plant. Finally, the European Union's Just Transition Fund has awarded €5 million in February 2024, for Itero's demonstration plant in the Netherlands. This facility will annually process 27 kt of mixed plastic waste into circular chemical feedstocks for virgin-quality plastics, while offsetting over 20 kt per annum of fossil resources, the equivalent of offsetting nearly 500 barrels a day. Itero's upcoming plant is further expected to create approximately 40 full-time jobs that support the transition from the petrochemical industry into a world-leading circular plastics hub[25].

BlueAlp. The first successful demonstration of what would become BlueAlp Technology later on, involved a pilot production plant of around 3 kt in Switzerland, in 2014. Six years of development later, the company launched their first commercial prototype plant, with Renasci & Den Hartog, Ostend, Belgium, in 2020. This facility is capable of processing around 21 kt of plastic feedstock per annum. BlueAlp has set the goal of being able to upcycle 1Mt of plastic waste per year by 2025. In 2021, Shell became shareholder, key customer, and technology partner of BlueAlp. Under this partnership, two new pyrolysis units will be built in the Netherlands with a capacity of 17 kt of plastic waste per annum. Finally, Borealis is another major player that has put its trust in the BlueAlp technology to help reach its circular goals[26,34].

Plastic Energy. Plastic Energy currently runs two commercial-scale recycling plants in Spain. The company's recycling plant in Almeria, employing the TAC™ process to convert end-of-life plastics into TACOIL™ that is in turn utilised for making new plastic packaging, has been operating since 2016. Plastic Energy's advanced recycling plant in Seville has been running since 2017. TACOIL™ from both these plants has been commercialised on the European market, into several, well-known consumer products. Besides these plant facilities, Plastic Energy announced the opening of their R&D labs in November 2022, following a decade of cooperation with Loughborough University. The labs are within the Loughborough University Science and Enterprise Park and include a pilot plant and will be used to test feedstocks and improve the quality of TACOIL™ produced by the TAC™ process[27].

In 2021, Plastic Energy, in a joint venture with TotalEnergies, announced the construction of a recycling plant at the Grandpuits site, in France. This follows an existing agreement with

TotalEnergies to be a TACOIL™ offtaker from Plastic Energy's plants in Spain. The plant will have the capacity to recycle 15 kt of plastic waste annually. In November 2021, Plastic Energy successfully completed a capital raise of €145 million from three separate investors, LetterOne, Axens and M&G; Morgan Stanley acted as financial advisor and placement agent to Plastic Energy on this capital raise. In October 2021, the company announced the final investment decision and start of construction of a new recycling plant in northern France. The plant, which will be adjacent to ExxonMobil's Notre Dame de Gravenchon petrochemical complex, will have a capacity of 25 kt of plastic waste per year, with plans to scale-up to 33 kt in the future. In January 2021, Plastic Energy announced a joint venture with SABIC to commence construction of an advanced recycling plant in Geleen, the Netherlands. This will be the first commercial unit to produce the company's flagship certified circular polymers, part of the TRUCIRCLE™ portfolio, which are made from the upcycling of mixed and used plastic. This plant will be able to process 20 kt of plastic waste per year, and the project is near completion. In November 2022, it was announced that Plastic Energy and SK Innovation's subsidiary for its green chemicals business, SK Geo Centric, plan to build a recycling plant in Ulsan, South Korea. This plant is expected to have a yearly capacity of 66 kt of plastic waste and will be located within SKGC's recycling cluster in Ulsan. In October 2023, PETRONAS Chemicals Group Berhad, has reached the final investment decision to construct Asia's largest advanced chemical recycling plant using Plastic's Energy pyrolysis technology. The plant, which will be located in Pengerang, Johor, is targeted to be operational by the first half of 2026 and will have a processing capacity of 33 kt per year[27].

Veolia Sheffield. The energy recovery facility of Veolia in Sheffield, UK was initiated in 2001 with a 35-year waste management contract, which was awarded to Veolia by the Sheffield City Council. Besides this, as the UK leader in environmental solutions, Veolia offers a broad range of waste, water, and energy management services designed to build the circular economy and safeguard scarce raw materials[28].

Carbios. At the pilot scale, Carbios' enzymatic technology has already led to the production of the first batches of transparent PET bottles from monomers obtained from the depolymerization of PET plastic waste and from polyester textile waste. In September 2021, an industrial demonstration plant relying on Carbios' bio-recycling process was completed within the site of the Michelin Group in Clermont-Ferrand, France. This plant enables the validation of the technical, environmental, and economic performance of Carbos' enzymatic PET recycling process; this a prerequisite for preparing the complete engineering documents of the process, required to construct and implement a first industrial unit. Regarding Carbios' enzymatic biodegradation technology, in September 2016, Carbios partnered with Limagrain Ingredients and the SPI fund (operated by Bpifrance) to create the joint venture Carbiolice. This company, mostly under the control of Carbios, uses the first technology licensed by Carbios to produce enzymatic granules for making biodegradable and biobased plastics. Currently, a manufacturing line that can process 50 kt of compostable PLA is operational. Moreover, multiple professional qualifications have been undertaken with major brands and plastics converters to help them implement Carbos' technology[29].

In November 2021, it was announced that Carbios, alongside partners T.EN Zimmer GmbH and Deloitte, received a €3.3 million grant (which includes €3 million for Carbios) from the European Commission. This financial support was given through the LIFE funding programme, a major financial tool supporting innovative solutions with low environmental impact and a track record of industrial deployment[29].

Agilyx Corporation. With about 20 years of experience, eight generations of technology released, the first commercial closed-loop plastic-to-plastic facility, and total investments of more than

$150 million, Agilyx is considered a leading player in the chemical recycling of plastic waste that is difficult to recycle. In a joint venture with Americas Styrenyx, Agilyx co-developed the world's first chemical recycler of used PS in 2019. The so-called Regenyx recycler, located in Tigard, OR, USA, demonstrated Agilyx's depolymerization technology and helped them establish a market for recycled styrene monomer and PS over the course of a 5-year project term. The project was successfully completed in 2024 and Agilyx decided to close the Regenyx facility and focus on larger, more economic projects. In June 2021, following pilot plant testing on PS recycling, Agilyx and Technip Energies announced the launch of the TruStyrenyx™ brand, which combines Agilyx's pyrolysis process and Technip Energies' purification technology, to deliver recycled styrene with exceptional high purity. In March 2023, Agilyx and INEOS Styrolution announced the development of a 100 tons per day TruStyrenyx™ chemical recycling facility in Channahon, IL, USA[30].

Covanta Holding Corporation. As of 2013, approximately 60% of Covanta's revenue came from selling waste disposal services and 25% from selling electricity produced by burning waste; the rest of its revenue resulted from metal recycling, construction, and other services. As of 2018, Covanta ran more than 40 waste-to-energy plants globally, in locations in Europe, North America, and China. Most of the relevant revenue came from long-term contracts with local governments or utility providers[35]. In 2018, Covanta has partnered with the Green Investment Group, and announced plans for further investments across the UK and Ireland. The first project had the capacity to divert 580 kt of waste from Dublin landfill annually, with a generating power capacity of 65 MW[36].

Geocycle. In June 2022, the Geocycle Hurst Farm platform at the Cauldon Cement Plant, Staffordshire, UK, was established by Geocycle UK. The new waste platform part of a £13.5 million investment was built adjacent to the cement works as part of a wider step-change to modernise the Cauldon plant, driving decarbonisation and circularity via increasing the utilisation of waste fuels and decreasing the amount of fossil fuels. The combined investment was estimated to save up to 30 kt of CO_2 per year. Through Geocycle's recycling and recovery technologies based on cement kiln co-processing, safe and sustainable recovery of approximately 100 kt of waste into the cement manufacturing process is possible annually[32].

SynPet Technologies. The company established its advanced R&D laboratory within the scope of MARGE Research-Development A.S. in September 2014.These laboratory facilities allow SynPet to continuously test their technology in a holistic manner, with the purpose of constantly improving the TCP™ process and the associated product quality. SynPet's pilot plant, located in Istanbul, Turkey, has been operational since 2018. This demo plant is the foundation for the company's long-term corporate development and establishment projects, and has been supported by industry experts since its initial stage. It is designed to perform tests, considered preparatory studies, for commercial plant investment, and has a feedstock capacity of 15 tonnes per day. In September 2023, SynPet has partnered with Kolmar Group AG to invest in the Port of Antwerp, one of Europe's largest and most dense petrochemical clusters. SynPet plans to deploy its chemical conversion technology assisted by Kolmar, who acquired a significant shareholding in SynPet at the closure of Synpet's first equity round[33].