

RECYCLING AND RECOVERY OF POST-CONSUMER PLASTIC SOLID WASTE IN A EUROPEAN CONTEXT

by

*Anke BREMS^{*1}, Jan BAEYENS² and Raf DEWIL¹*

¹Department of Chemical Engineering,
Chemical and Biochemical Process Technology and Control Section
KU Leuven (University of Leuven), Heverlee, Belgium
e-mail: anke.brems@cit.kuleuven.be, raf.dewil@cit.kuleuven.be

²School of Life Science and Technology,
Beijing University of Chemical Technology, Beijing, China
e-mail: baeyens.j@gmail.com

Abstract

The disposal of waste plastics has become a major worldwide environmental problem. The USA, Europe and Japan generate annually about 50 million tons of post-consumer plastic waste, previously landfilled, generally considered as a non-sustainable and environmentally questionable option. Landfill sites and their capacity are, moreover, decreasing rapidly, and legislation is stringent. Several European Directives and US legislation concern plastic wastes and the required management. They are briefly discussed in this paper.

New processes have emerged, i.e., advanced mechanical recycling of plastic waste as virgin or second grade plastic feedstock, and thermal treatments to recycle the waste as virgin monomer, as synthetic fuel gas, or as heat source (incineration with energy recovery). These processes avoid land filling, where the non-biodegradable plastics remain a lasting environmental burden.

The paper reviews these alternative options through mostly thermal processing (pyrolysis, gasification and waste-to-energy). Additional research is, however, still needed to confirm the potential on pilot and commercial scale.

Key words: *plastic waste, re-use, thermal valorisation, legislation, EU Directives, monomers*

1. Introduction

Plastics are light-weight, durable, and versatile, allowing their incorporation into a diverse range of applications. From helmets and protective clothing, to major components in automation and aviation, plastics are a crucial part of the world we live in. In recent years the environmental, social and economic impact of plastics has been the topic of the political agenda, with a focus on both the sustainable production, and the decoupling of adverse environmental effects from waste generation.

The disposal of waste plastics has become a major worldwide environmental problem. The USA, Europe and Japan generate about 50 million tons of post consumer plastic waste [1]. These waste products were previously dumped in landfill sites, a non-sustainable and environmentally questionable option. The number of landfill sites and their capacity are, moreover, decreasing rapidly and in most countries the legislation on landfills is becoming increasingly stringent. Two alternative disposal routes are possible: i.e. recycling or energy recovery.

As plastics are hydrocarbons, they possess a high calorific value in the order of 30 to 40 MJ/kg. They can thus be burned readily e.g. in municipal or dedicated waste incinerators with heat and power generation, or they can serve as a secondary fuel, replacing fossil fuels in production processes (e.g. cement kilns, blast furnaces). These thermal applications lead to a complete destruction of the plastics and need advanced pollution control measures [2]. Although an efficient waste management will reduce greenhouse gas emissions [3], the application of burning plastic waste will however not contribute to this reduction since replacing fossil fuels. Several studies have considered the environmental impact of landfilling and/or incineration [4-8]. Non-biodegradable materials, including plastics, will persist in the landfill, whereas biosolids will be anaerobically transformed into landfill gas, an energy resource. The short term impact of incineration is therefore more important since releasing more greenhouse gases than landfill does.

In recycling, two alternative methods are: (i) the secondary recycling or advanced mechanical recycling: the waste product is reprocessed by physical means into new plastic products, generally of a lower quality; and (ii) the tertiary recycling or feedstock recycling, where plastics are cracked into their constituent monomers, or in a hydrocarbon feedstock and fuel oil. This tertiary recycle process is gaining importance.

For physical recycling, it is of prime importance to have a separated, clean and dry plastic waste stream: sectors where the quality and homogeneity of the waste product are high, have high recycling rates, e.g. in agriculture (> 50%) and distribution (48%) [9].

The aims of the paper are hence threefold: (i) to critically review the current disposal and recycling options for plastic wastes; (ii) to assess the current EU-legislation and its impact on short and medium term plastic waste management; and (iii) to discuss the technical possibilities of different techniques.

2. Consumption and recycling of plastics

According to recent statistics compiled by Plastics Europe [9], the global and European procurement of plastic has grown substantially over the last 60 years. Global production and consumption have increased annually on average by 10%, from 1.5 million tons in 1950, to 245 million tons in 2007. The increase is attributed to an exponential growth of population and the increased use of plastic in the automotive, construction and packaging industries. However, the plastic industry was also hampered by the economic crisis with global production dropping to 230 million tons, and Europe dropping by 8% to 55 million tons in 2008 (fig. 1). In 2009 a slight recovery was seen with continued steady growth throughout 2011.

Plastics can be classified into two separate groups: thermoplastic and thermosetting plastics. The former have the unique ability that they can be remoulded. This is achieved through heating which causes the plastic to become malleable. Thermosetting plastics are rather different and cannot be remoulded once formed. If heated, the plastic decomposes and deteriorates opposed to becoming soft and formable. Every plastic type has its distinct characteristics, but some attributes are shared among all the plastics [10]:

- Plastics can be very resistant to chemicals and are consequently used to safely store many household solvents. However, there are specific solvents that can attack plastics.
- Plastics can be very good thermal and electrical insulators and are often used to house electrical wires and cooking utensils handles.
- Plastics are light in comparison to their volume and vary in strength. The choice of the monomer used in its structure will change the strength achieved, varying from the bristles on a brush to the tight weave on a bullet proof Teflon vest.
- Lastly, plastics can be produced in various forms and colours.

Thermoplastics contribute about 80% to the total plastic consumption, and are used for typical plastics applications such as packaging but also in other applications such as textile fibres and coatings. Thermosetting plastics are used in more demanding applications (e.g. for use at higher temperatures) and for derived applications such as adhesives.

Fig. 1 shows proportions of demand by resin type, with polyethylene, PE, and polypropylene, PP, accounting for approximately 50%. After use, the 11% polyvinyl chloride, PVC, demand can complicate recovery methods, as the high chlorine content of PVC associated with the undesirable formation of dioxins and furans during final disposal [2,12,13]. Often waste is separated into PVC deficient and PVC lean partitions. This is particularly relevant for energy recovery techniques.

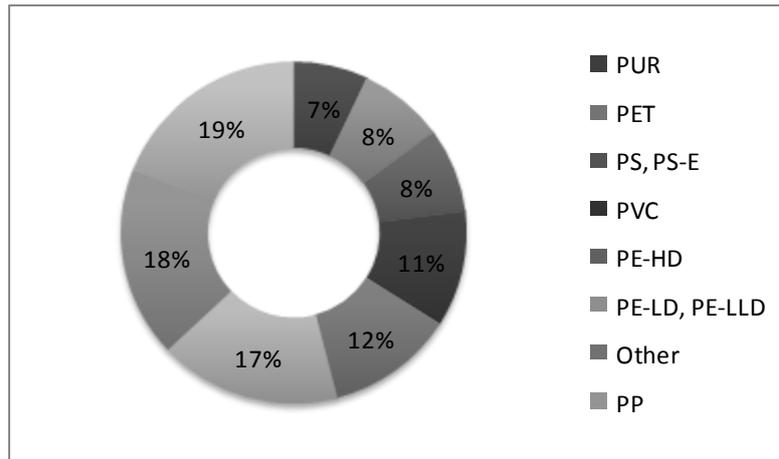


Figure 1. Plastic demand by resin - Adapted from Plastics Europe [9]

The main flow of common demand and waste plastics for the 27 member states of the EU, together with Norway and Switzerland, is illustrated in fig. 2.

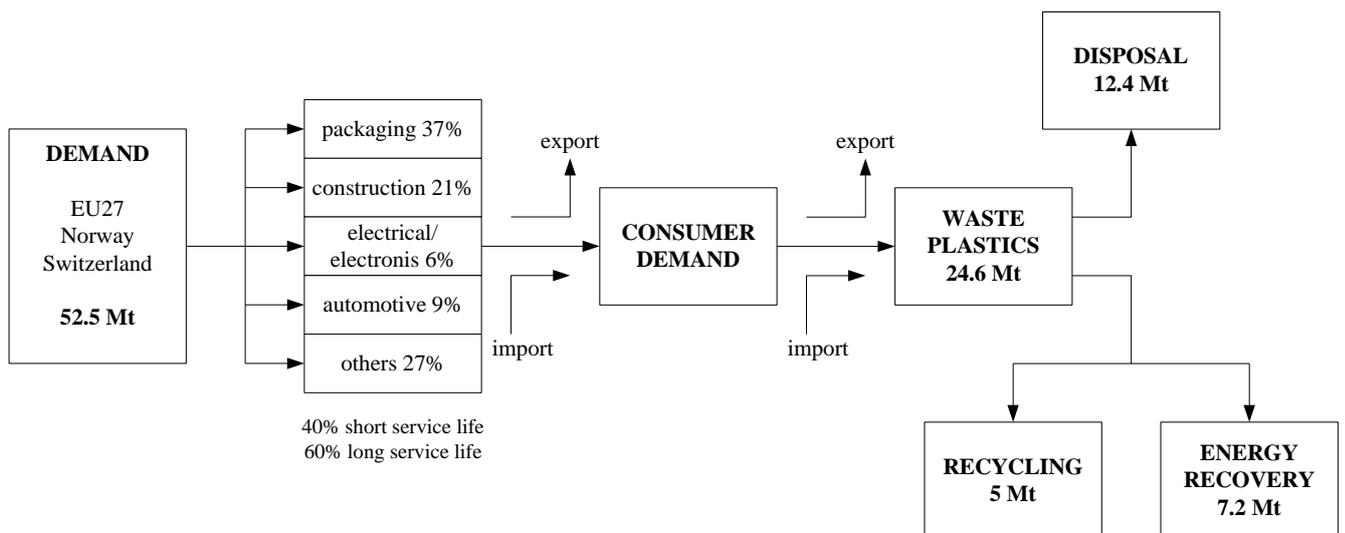


Figure 2. Plastics/waste plastics flow pattern - Adapted from Plastics Europe [9].

Packaging accounts for the largest share of the market segment with 37% of all plastics consumed; 36 % is distributed between the electrical and electronic, automotive and construction sectors [11]. Moreover, plastics are increasingly substituting other more traditional materials, such as glass, because of the weight benefit, flexibility and ease of processing. Although over 50% of all European goods are packaged in plastics, these plastics account for only 17% by weight of all packaging.

The second largest consumer is the building and construction industry, with a contribution of 21%. Plastics are used for a range of applications from insulation to piping, window frames to interior

design. The popularity is due to durability, strength, resistance to corrosion, low maintenance and aesthetically pleasing finish. 6% of the plastics are used in electrical and electronic equipment. Plastics are an indispensable material for this sector. It is a fact that many of today's new technical developments capitalise on the latest types of new generation plastics [9].

Other important plastic users are the automotive industry (9%), where plastics reduce car-weight and fuel consumption, agriculture (1.9%) and heavy industry (5.8%). The remaining percentage of plastics is used in other household and domestic applications.

Four recovery routes exist for waste plastics: primary (re-extrusion), secondary (mechanical recycling), tertiary (chemical recycling) and quaternary (energy recovery). As illustrated in fig. 2, about 50% of post-consumer plastic waste in Europe was directly recovered through primary and secondary routes (20.4%), or by way of resource recovery through tertiary and quaternary routes (31.5%). Just over half of this value, 24.6 million tons, is disregarded as waste, illustrating the relatively short life span of plastic products [9].

With growing pressure to improve recycling rates, the option of waste exportation to markets such as China and India is becoming popular. Low labour and energy costs make the importing of waste plastics economically viable for these markets. China absorbs over 70% of globally traded recovered plastics, approximately equivalent to 7 million tons in 2008 [9]. There is, however, a growing concern for Chinese Authorities that the quality of imported plastics is too low with particular concern for the standards of mixed plastic. This issue of contamination is a large barrier to plastic waste recovery methods as pre-treatment and separation techniques are both expensive and not fully developed. An increase in the international import standards may lead to a reduction of waste plastic that the plastic waste sector is able to export.

Augmented levels of waste plastic collection in Asia itself may moreover cause a fall in demand for imported plastics, resulting in difficulties to find a market for the plastic waste. However, the demand for plastic continues to grow at a high rate in Asia and, therefore, the increased collections may not displace the shortage of supply [14]. A further worry is the recent relative instability of international markets: the current demand for waste plastic will be greatly affected by fluctuations in the value of the Asian currencies, reducing the reliability of exporting waste.

The current trade in waste plastics is mainly driven by economical interests with little emphasis placed on the environmental impact of such waste management. However with the growing pressure to reduce greenhouse gas emissions, the exporting of waste plastic will come under greater scrutiny. Currently, there is great confusion within the European Union whether exporting waste plastic can be counted towards the European Commission determined recycling targets. Exports can only be counted if the standard of treatment of the exported plastic is 'broadly equivalent' to that in the EU [9]. Stricter controls on the treatment of exported waste plastic will further reduce the viability of this solution to waste management.

3. Legislation and plastic waste management

Mixed plastic solid waste is difficult to be treated or recycled due to its complex nature and composition, the structural deterioration of the polymeric components, and the contamination with various organic, inorganic or biological residues. High temperature incineration might cause hazardous emissions, and co-incineration is controlled by strict emission standards as e.g. set by the EU Hazardous Waste Incineration Directive [15].

The European recycling policy is derived from EU directives, which are in turn affected by global (e.g. the Kyoto Protocol on Climate Change) and European commitments. The EU directives set targets, such as an overall recovery percentage of waste to general principles such as a 'waste hierarchy'. Each country's government is responsible for implementing these directives. However, the ability to meet recycling targets is ultimately dependent on the behaviour of the consumer, retailers and producers. Recycling plastic waste is not a trivial task, as initially the plastic has to be pre-treated and separated, which is both time and cost intensive. Technology is slowly being introduced to sort plastics using various different techniques, including X-ray, infrared and electrostatics. However, the technologies are still very much in their infancy stage.

Several European directives (binding for all EU member states) concern the plastic waste issue and the requested waste management, and will be discussed below. Among the important legislation, the EC Directive (94/62/EC) on Packaging and Packaging Waste [16] has set a 15% material specific recycling target for packaging material by June 2001. This directive was revised in 2004. In 2008, directive targets were set for 60% recovery and 55% recycling rates for packaging. However, an estimated 5 million tons of packaging waste is still not being recycled. As a result, the government proposed that further, more demanding, targets should be set [17]. It is, therefore, possible to predict a rise in the amount of plastic packaging waste recovered in the coming years.

Another important Directive in European legislation is the revised EU Waste Framework Directive (WFD). This declares three main features that member states must bring into domestic legislation satisfying the EU directive by 12th December 2010: (i) the 'waste hierarchy' for waste prevention and management policy has to be applied; (ii) by 2015 separate waste collections for paper, plastic and glass (for both household and business waste) must be established; and (iii) a target of recycling 50% of household waste has to be met by 2020. Deviations from the waste hierarchy will be allowed if a better overall environmental outcome can be proven. It has also been clarified by the European Commission that mixed waste which is subsequently sorted at recycling facilities counts towards the separate collection directive [18].

Considering that prevention, recovery and recycling are key options in waste management, the European Plastics Industry is committed to promoting recovery waste management options. If the European Union is to meet the goals laid out in the EU Landfill Directive, which obliges member states to progressively reduce the landfill-amount of recyclable waste to 35% of the 1995 levels within 15 years, it is clear through exhaustive research and practical experience of the current status of the implementation of the Packaging and Packaging Waste Directive (PPWD) and related eco-efficiency

studies, that neither recycling nor energy recovery options alone are sufficient. Instead, a combination of both is needed to achieve the most eco-efficient and effective waste management solution [19].

Increased post consumer plastics recovery, and improved collection and separation infrastructures instigated good progress in the amount of plastics recovered, with e.g. improvements in recycling contributing to an 11.2% rise in recovery between 2001 and 2003. As a result, the amount of plastic waste dumped in landfills in 2003 was 61% of total collectible plastics waste, down from 63% in 2001 [9].

Another important source of plastic waste entering landfills comes from shredder residue (SR), and part of this plastic waste can also be targeted for recycling [20]. SR is the by-product of a process that reclaims the vast majority of ferrous and non-ferrous metals from post-consumer objects such as automobiles, fridges, washing machines etc. These waste products enter shredding facilities where they are size-reduced and metals are largely removed (> 90%) by over-band magnets and eddy current separators. The residual material is known as SR or ‘fluff’ (or ‘light-fluff’) and consists of a heterogeneous mixture of plastics, foam, rubber, etc. The need to recover more of this material is partly driven by the EU End of Life Vehicle Directive (ELVD) [20], and partly through a voluntary agreement by car manufacturers to incorporate a 25% level of recycled plastic back into cars. Similar developments on imposed increasing recycling also apply to other polymer waste, shredded tyres being a typical example, with landfilling of whole and shredded tyres being banned as e.g. applied in the U.K. since 2006 [21].

Plastic waste is specifically problematic owing to the high volume/weight ratio: as such it is not an attractive material for collection and recycling, and costs of transportation, of reprocessing, and value of virgin feedstock all have an impact on the ultimate price of the recycled polymer material [19]. Domestic waste remains the main source of waste plastics, about two thirds of the total generated. Distribution and industrial sectors are the second important source.

One should remember that plastics are mostly non-biodegradable and will be present in landfills for a very long time, with only 1-3% of the hydrocarbon content degraded during a considered time period of 100 years. Recycling is hence a must [22,23].

Although the present paper targets the European context, it is interesting to compare the European and USA approach.

The situation in the USA is more complex, since federal laws and state/district laws are put into place, whereas the Environmental Protection Agency EPA also plays an important role in developing appropriate solid waste management strategies [24]. An update of the waste and recycling facts is presented by the Clean Air Council [25] and by Zero Waste America [26].

One of the EPA’s publications, “The solid waste dilemma: an agenda for action”, addresses the EPA’s goal of managing 25% of the US’ municipal solid waste through source reduction and recycling [24].

While the 25% goal is not a federal law, the EPA both provides recommendations to reach that goal, and published numerous reports regarding waste reduction and recycling.

The general guidelines for the waste management programme envisioned by Congress are set by the Resource Conservation and Recovery Act (RCRA), being given a congressional mandate directing EPA to develop a comprehensive set of regulations to implement the law, and determine the requirements for the Agency and the regulated community. As far as waste regulators are concerned, they are contained in title 40 of the Code of Federal Regulations (CFR) parts 239 - 259 (parts 260 - 279 cover hazardous waste regulations). The relevant list of solid waste regulations with links to the regulatory text includes [27]:

- part 239: Requirements for state permit programme determination of adequacy
- part 240: Guidelines for the thermal processing of solid wastes
- part 243: Guidelines for the storage and collection of residential, commercial and institutional solid waste
- part 246: Source separation for materials recovery guidelines
- part 247: Comprehensive procurement guideline for products containing recovered materials
- part 254: Prior notice of citizen suits
- part 255: Identification of regions and agencies for solid waste management
- part 256: Guidelines for development and implementation of state solid waste management plans
- part 257: Criteria for classification of solid waste disposal facilities and practices
- part 258: Criteria for municipal solid waste landfills

In regulations proposed under the federal Clean Air Act [25], the EPA proposed that waste-to-energy incinerators are obliged to reduce the amount of garbage they burn by 25% through recycling and composting. The EPA sees this plan as a way to cut toxic substance emissions, reduce the amount of landfilled ash, and promote its goal of 25% national waste reduction. The national waste reduction and recycling legislation are clearly on the move as a result of organised opposition to land disposal of solid waste and general public awareness of the need to reduce the amounts of waste in general. The incentive for the legislation was in a lot of cases the lack of available landfill capacity, the not-in-my-backyard (NIMBY) syndrome, the escalating expense of waste disposal, and the environmental consequences of disposal [24,28]. Most states have already issued necessary laws, whereas others have replicated portions of laws from other states that have developed viable solutions. Solutions proposed include recycling, composting, and waste reduction strategies. The federal government will moreover need to provide the legislation for waste reduction to some rural states that have not yet developed the needed waste reduction legislation.

4. Overall plastic solid waste treatment

As stated before, plastic solid waste (PSW) treatment can be categorised under four classifications. Each individual method provides a unique set of advantages making it particularly suited and beneficial to a specific location, application or product requirement [29]. The purpose of recycling is to minimise the consumption of finite natural resources. This is specifically relevant in the case of plastics which account for 4 - 8% of the global oil production [29]. Re-using plastics is the favourable course of action as it does not require energy or resources and conserves fossil fuels. The CO₂, NO_x and SO₂ emissions associated with plastic production are also negated if the plastic is re-used [29]. The most appropriate recovery method is chosen considering the environmental, economic and social impact of a particular technique. Fig. 3 illustrates the position of each recycling method within the production chain.

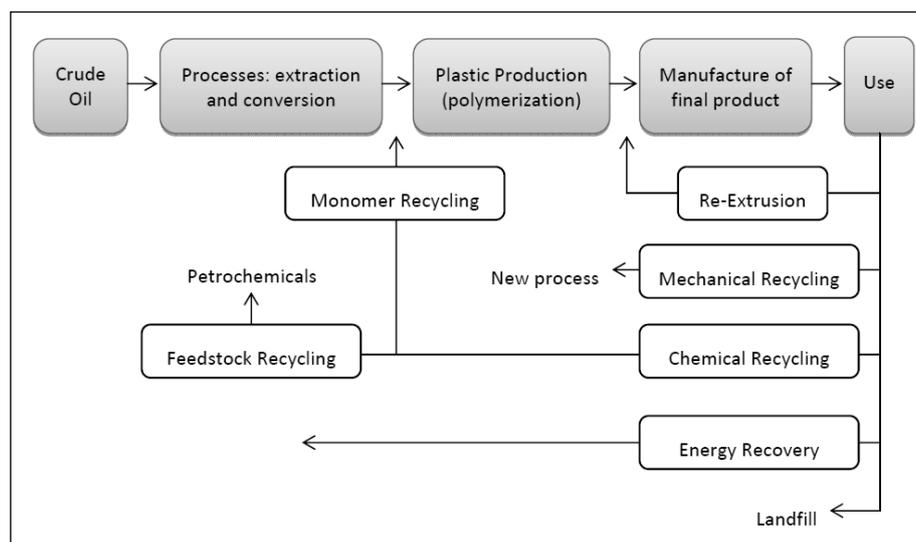


Figure 3. Schematic of recycling methods position within the processing line - Adapted from Al-Salem et al. [30]

4.1. Primary recycling

Primary recycling involves the re-introduction of clean, single polymer waste into the extrusion cycle, predominantly applied within the processing line [30]. Similarly, mechanical recycling is mostly practiced by manufacturers thus applying the pre-consumer, clean waste.

4.2. Mechanical recycling

According to the European plastics industry [9], the environmentally and economically most favourable recycling technique is mechanical recycling. This method was the largest recycling method in 2002, contributing for 51% to the overall recycling, and is the second largest recovery technique for plastic waste after energy recovery. This technique directly recovers clean plastics for reuse in the manufacturing of new plastic products: the difficulties are mainly related to the degradation of recyclable material and heterogeneity of plastic wastes [30].

Especially pre-consumer plastic waste is suitable for mechanical recycling. The pre-consumer residues only include the material generated by industry, either in the production of the polymers or when using or transforming them into the final product. The pre-consumer products generally consist of a unique feedstock, and are well identified, clean and homogeneous [9,30].

In contrast, the post-consumer residues are a mixture of different plastics generally contaminated with dirt or other residues thus making recycling far more difficult, although feasible.

4.3 Feedstock recycling

4.3.1. Generalities

Feedstock recycling comprises various advanced recycling technologies to turn solid polymeric wastes into high value feedstock that can be used as raw materials in the production of new petrochemicals and plastics, without any deterioration in their quality and without any restriction regarding their application. Feedstock recycling has in theory a great potential to boost plastics waste recovery levels [9]. These processes involve the use of moderate to high temperatures to break the structured bonds of the polymer. They can be carried out in an oxygen-lean environment (pyrolysis), using a high partial pressure of hydrogen (hydrocracking), or with a controlled amount of oxygen (gasification) [29]. These technologies can be further roughly classified according to the residence time of both solid and gas phase in the reactor, e.g. a long residence time of the solids and a short residence time of the gas in a bubbling fluidized bed (BFB), or a short residence time of both solids and gas phases in a circulating fluidized bed (CFB). Thermal degradation processes allow the obtainment of a number of constituting molecules, combustible gases and/or energy, with the reduction of landfilling as an added advantage [31].

4.3.2. Pyrolysis

A decomposition process carried out in the absence of air or in an oxygen-lean environment is termed pyrolysis or thermal cracking. It is a flexible process and thus especially useful when dealing with heterogeneous wastes such as comingled waste or automotive shredder residue [32,33].

Using pyrolysis, the plastic waste is converted into gases, a mixed liquid hydrocarbon fraction (the so-called pyrolytic oil) and a solid residue (char). Since hydrogen and oxygen are absent during the process, usually high molecular weight and hence high boiling fractions are obtained. These are further processed and refined, resulting in petrochemical feedstock such as naphta. Tab. 1 summarises the main products of thermal decomposition of separate polymer processes [12,32]. A summary of the obtained products after laboratory-scale pyrolysis of various polymers is presented in tab. 2 [34]. These data reveal that within the group of analysed polymers, only PMMA and polystyrene (PS) can be considered for monomer recovery. The other polymers are sources of pyrolytic fuels (gas, oil, waxes).

Table 1. General chemical recycling products of separate resins - Adapted from Sheirs et al. [32] and Panda et al. [12]

resin	low-temperature products	high-temperature products
PE	waxes, paraffin, oils, α -olefins	gases, light oils
PP	vaseline, olefins	gases, light oils
PVC	HCl, benzene	toluene
PS	styrene	styrene
PMMA	MMA	
PTFE	monomer	TFE
PET	benzoic acid, vinyl terephthalate	
PA-6	caprolactam	

Table 2. Pyrolysis of polymeric waste and hydrocarbon raw materials, detailed analysis [34]

Feedstock	Pyrolysis temperature (°C)	Gas (wt%)	Oil (wt%)	Solid Residue (wt%)	Other products (wt%)
Polyethylene (PE)	530	7.6	50.3	0.1	42 waxes
Polystyrene (PS)	580	9.9	24.6	0.6	64.9 styrene
Polyester	768	50.8	40.00	7.1	2.1 H ₂ O
Polyvinylchloride (PVC)	740	6.8	28.1	8.8	56.3 HCl
Polymethylmethacrylate (PMMA)	450	1.25	1.4	0.15 C	97.2 MMA

Several technical designs of pyrolysis reactors have been studied in the literature. Most authors [35-38] conclude that a fluidized bed reactor is the most favourable option. This method possesses a number of advantages which yield a more uniform product and a higher conversion rate. In-bed reduction of gaseous pollutants, such as SO₂ or HCl, moreover offers additional benefits [39].

The reactor is generally filled with sand particles acting as a heat transfer material. When introduced in the reactor, the plastics quickly melt and coat the sand particles with a thin layer of polymer. This amalgam undergoes thermal cracking and produces lighter hydrocarbons which leave the reactor with the fluidizing gas. This mechanism results in a uniform distribution of the polymers and excellent heat and mass transfer properties, resulting in a constant pyrolysis temperature and thus highly controlled polymer cracking and a minimisation of side reactions [40]. The process has a high efficiency for conversion of plastic waste to petrochemical products, with an additional 10-15% used as fuel gas in the process itself.

When dealing with condensation polymers such as polyesters, polyamides, polyethylene terephthalate (PET) and polymethylmethacrylate (PMMA), it is possible to use a pyrolysis reaction to transform the plastic into its original synthesis monomers [1,35]. This process is termed chemical recycling or depolymerisation. Depolymerisation of addition polymers is more difficult, although some studies have shown its feasibility [29,32,37,38].

The efficiency of these processes can be very high. Kaminsky et al. [38] reported a recovery of 75% styrene and 10% oligomers when feeding polystyrene to a fluidized bed reactor and a recovery of 98% when using PMMA as feed.

A typical pyrolysis flowsheet for waste plastics using a bubbling fluidised bed reactor, as developed by the authors, is illustrated in fig. 4. The preliminary mass and energy balance is illustrated in fig. 5 for e.g. polystyrene. A portion of the gas phase products is shown to feedback into the pyrolysis process as a source of energy for the conversion. The figure shows the proportion of products that can be utilised as a fuel and as a marketable product for the chemical industry. As can be seen, an input feed rate of 1 ton/hour has been assumed and an average product balance is given, assuming a total energy content of 38.5MJ per kilogram of plastic feed. There is an opportunity to utilise almost all this energy as the gas phase can be burned or used directly as a heat source. Waste heat on site may be used to raise steam or pre-heat the input steam required for the process as well as for space heating.

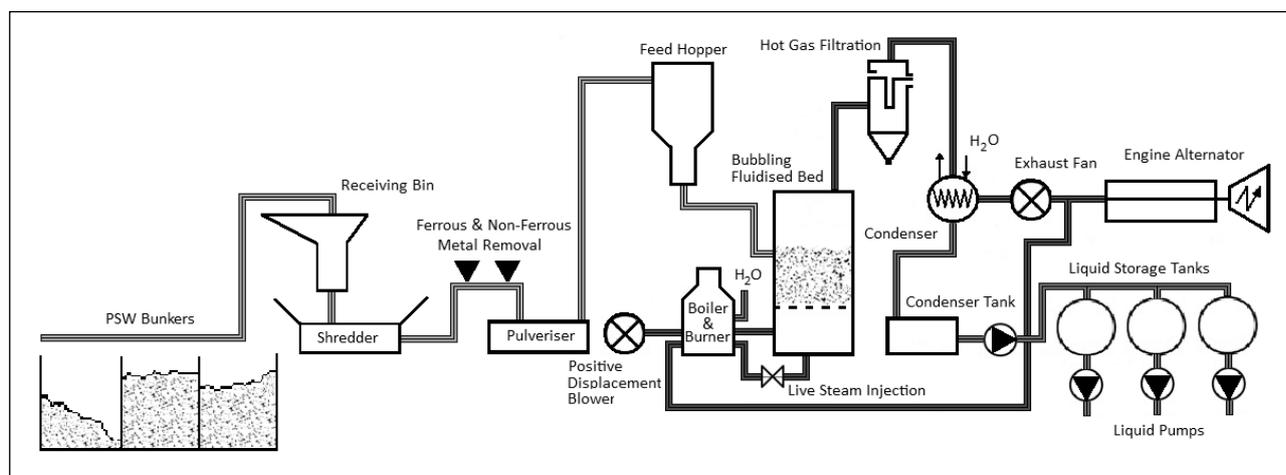


Figure 4. Flowsheet for waste plastics

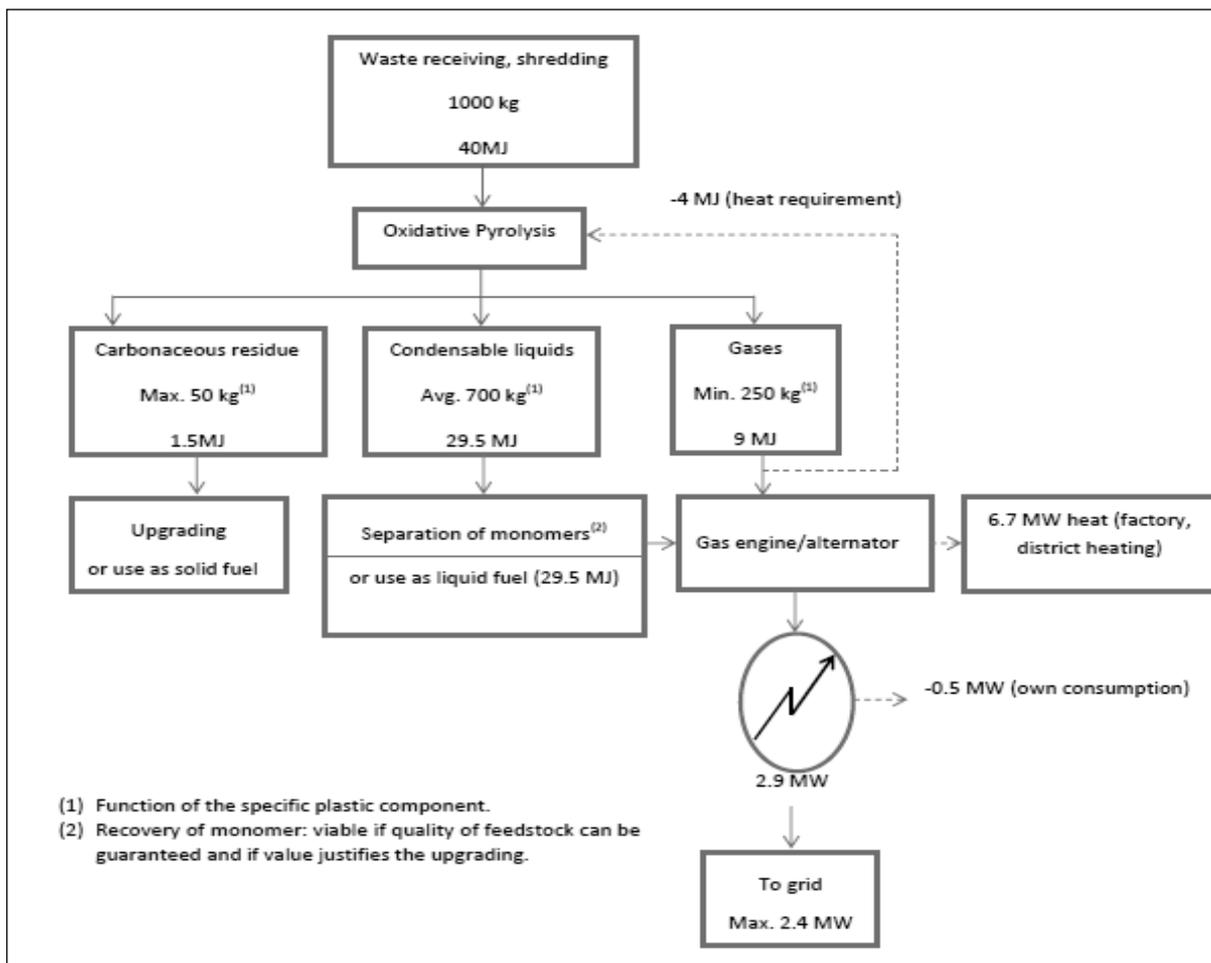


Figure 5. Mass and energy balance

The economical favourability of this process for mixed plastics is shown in an economic evaluation of the above depolymerisation plant, with a capacity of 8000 tons/year. This evaluation is summarised in tab. 3.

Table 3. Economic evaluation of mixed plastics depolymerisation

Capacity	8000 tons/year
Investment	£ 3.5 million
Sale of liquids	£ 2.0 million
Sale of electricity	£ 3.4 million
Revenue	£ 5.4 million
Operating costs	£ 1.2 million
Net return	£ 4.2 million

Depolymerisation is even more attractive when dealing with rather expensive polymers such as PMMA. Various processes for recycling PMMA are described in the literature [34,40]. The most prominent ones are the extrusion system, the molten lead bath system and the fluidized bed process. Experiments of Smolders and Baeyens [34] concluded that a fluidized bed has superior properties.

4.3.3. Hydrocracking

A second feedstock recycling process for plastic waste is known as hydrocracking, as described in detail by Al-Salem et al. (2010) and Scheirs (1998) [29,32]. In this process, plastic waste is exposed to a hydrogen atmosphere at pressures in excess of 100 atm, and converted into fragments of hydrocarbons, in appearance and composition similar to crude oil [29,32].

In hydrocracking, heat fractures molecules into highly reactive free radicals (cracking) that are saturated with molecular hydrogen (hydrogenation) as they form. Cracking and hydrogenation are energetically complementary processes since the cracking reaction is endothermic while hydrogenation is exothermic. Thus the surplus of heat that is produced can be handled by employing cold hydrogen as a quench for this reaction [30]. The partial pressure of hydrogen must be high enough to suppress undesirable coking or re-polymerisation. Possibly, a catalyst can be used for enhancing the hydrocracking process [41].

Despite the need to operate at high pressure with H₂ as reactant, hydrocracking offers advantages, e.g. (i) high-value products are obtained, (ii) the synthetic crude oil can be used without any difficulty in refineries (better feedstock than pyrolysis and gasification), (iii) troublesome hetero-atoms (i.e. Cl, N, O, S) are handled excellently and (iv) no toxic products such as dioxins are produced in or survive the process [30,32].

4.3.4. Catalytic cracking

The addition of a catalyst to thermal cracking can enhance the conversion and product quality. Catalytic cracking facilitates the selective degradation of plastic waste producing lighter fuel fractions compared to purely thermal cracking [29]. Early studies have been mostly limited to pure polyolefines and fresh, pure acid catalysis, predominantly zeolites. Panda et al. [12] discuss the advantages of the presence of a catalyst to significantly reduce degradation temperatures and reaction times resulting in increased conversion rates, narrower hydrocarbon product distributions and increased gaseous product yield.

4.3.5. Gasification

Gasification or partial oxidation of plastic waste is performed with the controlled addition of oxygen. The process essentially oxidises the hydrocarbon feedstock in a controlled fashion. The primary

product is a gaseous mixture of carbon monoxide and hydrogen, with minor percentages of gaseous hydrocarbons also formed. This gas mixture is known as syngas and can be used as a substitute for natural gas or in the chemical industry as feedstock for the production of numerous chemicals. The inorganic ash residue becomes bound in a glassy matrix and can be used as a component in concrete and mortar due to its high acid resistance [29,32,36,37]. A hydrogen production efficiency of 60-70% from polymer waste has been reported for a two stage pyrolysis and partial oxidation process [42]. Gasification is an attractive option since it prevents the formation of any dioxins and aromatic compounds. Gasification efficiently utilises the chemical energy and recoverable raw materials inherent in unsorted domestic waste, industrial and special waste (e.g. medical waste), and is capable of transforming almost all of the total waste input into technically usable raw materials and energy [32]. Co-gasification of biomass with polymers has also been shown to increase the amount of hydrogen produced while the CO content reduced [43]. A 40 MW fluidized bed gasifier has been installed by Corenso in Varkaus (Finland) for processing polyethylene plastics with metallic aluminium recovery from recycling of Tetrapak cartons. A typical circulating fluidized bed gasifier is illustrated in fig. 6 [44].

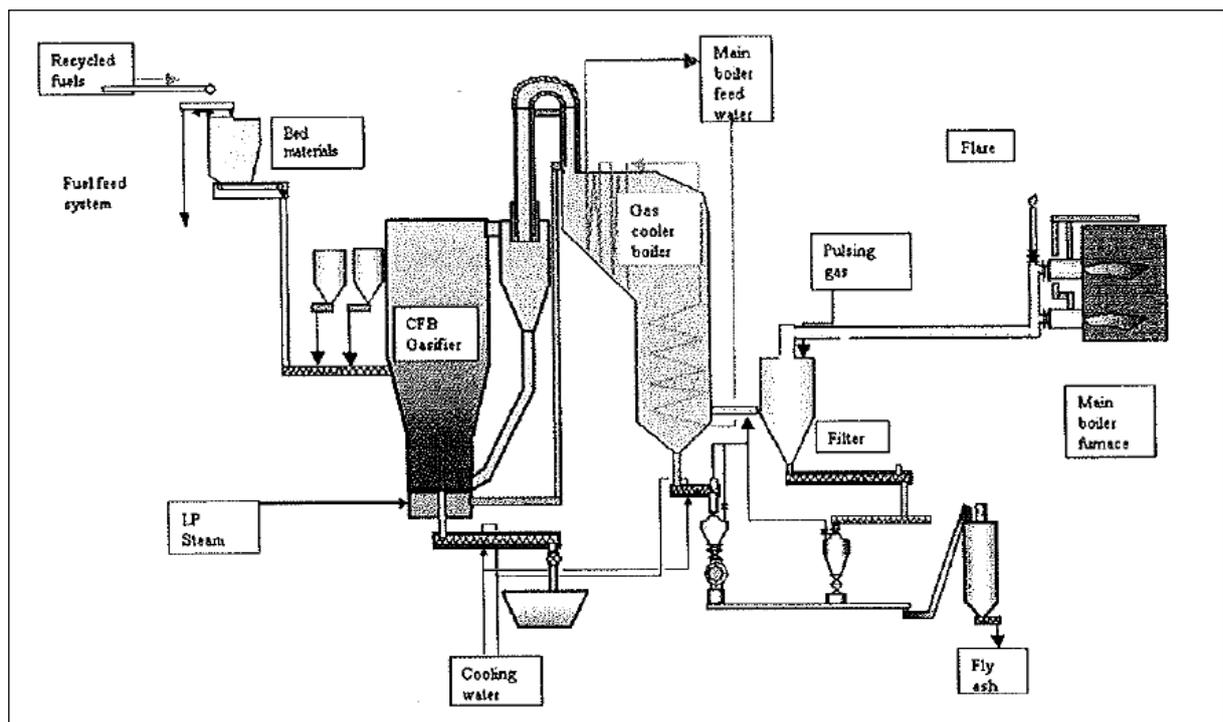


Figure 6. Fluidised bed gasification plant

5. Incineration with energy recovery

Energy recovery remains the most common recovery route for post-user plastics waste in Western Europe with 29.2 % of total collectable plastic waste dealt with [9]. In the past, concern around the poor environmental performance and emissions from old incinerators meant that this form of re-use was often met with opposition. However, strict legislation has ensured that energy recovery is now endorsed as an environmentally sound option. The incineration of plastic waste in the European Union is governed by Directive 2000/76/EC on the incineration of waste [45].

The heat content of plastics compares favourably with that of traditional fuels such as heating oil and natural gas and thus plastics can be conveniently used in waste-to-energy plants, particularly if they cannot be mechanically recycled because of excessive contamination, separation difficulties, or polymer property deterioration.

The plastic waste can be burned as such or can be co-fired as a mixed combustible fraction for use in solid fuel fired boilers and power plants when heat is recovered, possibly with power generation [29,30,36]. The use of plastic waste as a fuel in cement and lime kilns is widely applied (utilised as a partial substitute for coal or coke) [36,46].

The energy option is interesting when mechanical recycling is both economically and environmentally costly: due to the lightweight and diverse nature of smaller plastic products (such as films, pouches, yoghurt cups, blister trays etc.), collection, sorting and mechanical recycling is simply no viable option [29].

Plastic waste incineration with energy recovery offers major advantages: (i) a reduction in the mass of waste by 90%; (ii) potentially harmful substances in the waste stream are destroyed; (iii) the inorganic fraction of the waste is essentially mineralized by incineration to an inert slag, which can be used as a raw material in the construction of roads; (iv) it is an ideal route for recycling mixed or heavily polluted polymeric substances and (v) it is the best and safest method for handling hazardous plastic waste such as medical plastic waste or hazardous-goods packaging.

Co-incineration of energy-rich plastic and low-calorific municipal solid waste has a positive effect on the incineration process where plastics are a benefit as a fuel that is low in ash and moisture, and an energy source for efficient destruction of pollutants [47].

Mono-combustion of plastic waste on its own is often used to produce steam for heat and power generation. Modern combustion technologies provide a high degree of combustion control and automation and are equipped with sensing technology to optimize air/fuel demands [29,36].

Whereas mono-combustion requires specially designed boilers, co-combustion can be performed in existing (multi-fuel boilers). Burning 100% waste plastics in a grate fired boiler can be hampered by an uneven distribution of air in the bed and the occurrence of hot-spots, both of which are the result of the inhomogeneous nature of the plastic feedstock. As a consequence such waste incinerators require

extensive flue gas cleaning systems to comply with the strict emission regulations. On the other hand, if the plastic waste is sorted and shredded and then evenly mixed with a primary fuel (e.g. coal or peat), the combustion is more efficient and no extensive flue gas cleaning is required. This is also true when mixing plastic waste with other municipal solid waste prior to incineration.

The presence of brominated fire retardants (BFR) could cause problems because during their incineration PCBD/F's are formed. Tange and Drohmann [48] demonstrated, however, that the production of these dioxins or dioxin-like products is not increased by the co-incineration of BFR-containing plastics and that the emissions remain within the legal standards for these processes.

The use of fluidized bed combustion is often advantageous and increasingly used [36].

6. Summary of the conversion routes

A summary comparing pros and cons of each PSW conversion route is given in tab. 4.

Table 4. Summary of the processes used for the conversion of plastic solid waste

process	conversion product	comments
Recycling	feedstock polymer	- useable for homogeneous plastic waste
Incineration with energy recovery	energy in the form of steam	- combined use of electricity generated and residual heat - stringent air-quality regulations for stack emissions
Gasification	energy in the form of low-energy gas	- mostly used for power and heat generation - technology proved on pilot scale
Pyrolysis	energy in the form of gas and char, possible recovery of monomers	- technology proved on pilot scale - further upgrading/recovery of value-added products to be developed
Hydrocracking Catalytic cracking	hydrocarbons, in composition similar to crude oil	- need of H ₂ and high pressure - technology on laboratory scale only

7. Environmental benefits, sustainability and R&D potential

The development of technologies to convert plastic waste into its valuable constituting chemicals is of primary importance, methanolysis of e.g. PET being an example of a chemical route. Another possibility is to thermally “crack” the carbonaceous materials into monomers that can be reused in plastic manufacturing. The latter process, moreover, enables the recovery of inorganic compounds like cadmium, lead, glass or other valuable minerals from the pigments or strengtheners added to the plastic. These technologies already exist, but further research is needed to prove their economic viability. Recently, the pyrolysis of waste PET-bottles has been investigated with emphasis on the production of a carbonaceous residue with properties of activated carbon [35]. This route needs further investigation both to optimize the process yields and adsorption activity of the char residue, and to assess the applicability to other plastic wastes, with special emphasis on mixed plastics.

8. Conclusions

This paper provided an overview of the waste management options for plastic wastes. Since landfill, which used to be the only disposal route for plastic waste, is no longer a viable option, alternative disposal or recycling options have become necessary.

Two sustainable alternative disposal routes are feasible: recycling and incineration with energy recovery.

In recycling, two major routes are possible. The mechanical recycling reprocesses the waste plastic by physical means into new plastic products. This option is only feasible when dealing with a homogeneous waste stream. When different sorts of plastics are mixed, a feedstock recycling is appropriate. This method converts the plastic waste into new feedstock which can be used as a fuel of in the production of new plastics or chemicals. Another option is the incineration of the plastic waste. Since plastics possess a high calorific value, they can be burned readily. Further research is needed, especially in the plastic waste to feedstock option. It is however expected that only a combination of different disposal routes will achieve the most eco-efficient, effective waste management solution.

9. Acknowledgments

The research was partly funded by the Fundamental Research Funds for the Central Universities RC1101 (PR China) and partly funded by Project KP/09/005 (SCORES4CHEM Knowledge Platform) of the Industrial Research Council of the KU Leuven (Belgium).

10. Nomenclature

BFR	brominated fire retardants
EC	European Commission
ELVD	End of Life Vehicle Directive
EPA	Environmental Protection Agency
EU	European Union
NIMBY	Not-in-my-backyard
PCBD	polybrominated dibenzodioxins
PCBF	polybrominated dibenzofurans
PE	polyethylene
PE-HD	polyethylene - high density
PE-LD	polyethylene - low density
PE-LLD	polyethylene - very low density
PET	polyethylene terephthalate
PMMA	polymethylmethacrylate
PP	polypropylene
PPWD	Packaging and Packaging Waste Directive
PS	polystyrene
PSW	plastic solid waste
PUR	polyurethane
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
SR	shredder residue
USA	United States of America
WFD	Waste Framework Directive

11. References

1. Baeyens, J., Brems, A. and Dewil, R., Recovery and recycling of post-consumer waste materials - Part 2. Target wastes (glass beverage bottles, plastics, scrap metal and steel cans, end-of-life tyres, batteries and household hazardous waste), *International Journal of Sustainable Engineering*, Vol. 3, No. 4, 2010, pp. 232 - 245.
2. Everaert K. and Baeyens J., The formation and emissions of dioxins in large scale thermal processes, *Chemosphere*, Vol. 46, No. 3, 2002, pp. 439 - 448.
3. Vucinic A.A., Hublin A. and Ruzinski N., Greenhouse gases reduction through waste management in Croatia, *Thermal Science*, Vol. 14, No. 3, 2010, pp. 681-691.
4. Raggosnig A.M., Wartha C. And Pomberger R., Climate impact analysis of waste treatment scenarios: Thermal treatment of commercial and pretreated waste versus landfilling in Austria, *Waste Management and Research*, Vol. 27, No. 9, 2009, pp. 914-921.
5. Obersteiner G., Binner E., Mostbauer P. and Salhofer S., Landfill modeling in LCA: A contribution based on empirical data, *Waste Management*, Vol. 28, No. 8, 2007, pp. S58-S74.
6. Morris J., Comparative LCA's for curbside recycling versus either landfilling or incineration with energy recovery, *International Journal of Life Cycle Assessment*, Vol. 10, No. 4, 2005, pp. 273-284.
7. Lea W.R., Plastic incineration versus recycling: A comparison of energy and landfill cost savings, *Journal of Hazardous Materials*, Vol. 47, No. 1-3, 1996, pp. 295-302.
8. Eriksson O. and Finnveden G., Plastic waste as a fuel: CO₂ neutral or not?, *Energy and Environmental Science*, Vol. 2, No. 9, 2009, pp. 907-914.
9. Plastics Europe, The compelling facts about plastics 2009: An analysis of plastics production, demand and recovery for 2009 in Europe, *Published by the Association of Plastic Manufacturers in Europe*, 2010.
10. Crawford R.J., *Plastics Engineering*, Elsevier Butterworth-Heinemann, Oxford, 1998.
11. KINGFA, Plastic consumption, *available online from <http://www.kingfa.co.uk/>*, 2008.
12. Panda, K., Achyut, I., Singh, R.K. and Mishra, D.K., Thermolysis of waste plastics to liquid fuel: a suitable method for plastic waste management and manufacture of value-added products - a world perspective, *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 1, 2010, pp. 233 - 248.
13. Everaert K. And Baeyens J., Correlation of PCDD/F emissions with operating parameters of municipal solid waste incinerators, *Journal of the Air and Waste Management Association*, 51(5), 2001, pp. 718 - 724.
14. WRAP, Material change for a better environment: domestic mixed plastic packaging waste management options, *online available from <http://www.wrap.org.uk/>*, 2006.
15. European Union, EU Directive on Hazardous Waste Incineration, *Directive 2000/76/EC of the European Parliament and the Council, December 4th*, 2000.
16. European Communities, *European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste*; Official Journal of the European Communities, L 365/10, 1994.
17. The revised EU Waste Framework Directive: A consultation by DEFRA and the Welsh Assembly Government, *online available from <http://www.defra.gov.uk/>*, 2010

18. European Communities, *Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste*; Official Journal of the European Communities, L182, 1999.
19. Ambrose, C.A.; Hooper, R.; Potter, A.K. and Singh, M.M., Diversion from landfill: quality products from valuable plastics, *Resources, Conservation and Recycling*, Vol. 36, No. 4, 2002, pp. 309-318.
20. European Communities, *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles*; Official Journal of the European Communities, L269/34, 2000.
21. UK Environment Agency (EA), Key facts about tyres, available at www.environment-agency.gov.uk/business/topics, 2009.
22. Al-Salem, S.M.; Lettieri, P. and Baeyens J., Recycling and recovery routes of plastic solid waste (PSW): A review, *Waste Management*, Vol. 29, No. 10, 2009, pp. 2625-2643.
23. Holmgren, K. and Henning, D., Comparison between material and energy recovery of municipal waste from an energy perspective: A study of two Swedish municipalities, *Resources, Conservation and Recycling*, Vol. 43, No. 1, 2004, pp. 51-73.
24. EPA (US Environmental Protection Agency), <http://www.epa.gov>, retrieved on 18/06/2011.
25. Clean Air Council, <http://www.cleanair.org/Waste/WasteFacts.html>, retrieved on 18/06/2011.
26. Zero Waste America, Waste and Recycling Data, maps and graphs (1988 - 2008), <http://zerowasteamerica.org/statistics.htm>, retrieved on 18/06/2011.
27. EPA (US Environmental Protection Agency), non-hazardous waste regulations, <http://www.epa.gov/epawaste/laws-regs/regs-non-haz.htm>, retrieved on 18/06/2011.
28. Lund, H.F., McGraw-Hill Recycling Handbook, *New York, McGraw-Hill, Inc.*, 1993.
29. Al-Salem, S.M.; Lettieri, P. and Baeyens, J., The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals, *Progress in Energy and Combustion Science*, Vol. 36, No. 1, 2010, pp. 103-129.
30. Al-Salem, S.M., Lettieri, P. and Baeyens, J., Recycling and recovery routes of plastic solid waste (PSW): a review, *Waste Management*, Vol. 29, No. 10, 2009, pp. 2625 - 2643.
31. Mastral, J.F.; Berruoco, C. And Ceamanos, J., Theoretical prediction of product distribution of the pyrolysis of high density polyethylene, *Journal of Analytical and Applied Pyrolysis*, Vol. 80, No. 2, 2007, pp. 427-438.
32. Scheirs, J., In *Polymer recycling*, Wiley: New York, 591 p., 1998.
33. Paolucci M., De Filippis P. and Borgianni C., Pyrolysis and gasification of municipal and industrial wastes blends, *Thermal Science*, Vol. 14, No. 3, 2010, pp. 739-746.
34. Smolders, K. and Baeyens, J., Thermal degradation of PMMA in fluidised beds, *Waste Management*, Vol. 24, No. 8, 2004, pp. 849-857.
35. Brems, A.; Vandecasteele, C.; Baeyens, J. and Dewil, R., Polymeric cracking of waste polyethylene-terephthalate to chemicals and energy, *International Journal of Sustainable Engineering*, Vol. 3, No. 4, 2010, pp. 232-245.
36. Vermeulen, I., Van Caneghem, J., Block, C., Baeyens, J. and Vandecasteele, C., Automotive shredder residue (ASR): reviewing its productions from end-of-life vehicles (ELVs) and its recycling, energy and chemicals valorization, *Journal of Hazardous Materials*, in press, 2011.
37. Arena, U. and Mastellone, M.L., In *Feedstock recycling and pyrolysis of plastic wastes*; Scheirs, J.; Kamimnsky, W., Ed.; Wiley: Hoboken, NJ, 2005.

38. Kaminsky, W.; Predel, M. and Sadiki, A., Feedstock recycling of polymers by pyrolysis in a fluidised bed; *Polymer Degradation and Stability*, Vol. 85, No. 3, 2004, pp. 1045-1050.
39. Cojbasic Z.M., Nikolic V.D., Ciric I.T. and Cojbasic L.R., Computationally intelligent modelling and control of fluidised bed combustion process, *Thermal Science*, Vol. 15, No. 2, 2011, pp. 321-338.
40. Kaminsky, W. and Eger, C., Pyrolysis of filled PMMA for monomer recovery. *Journal of Analytic and Applied Pyrolysis*, Vol. 58, 2001, pp. 781-787.
41. Walendziewski, J. and Steininger; M., Thermal and catalytic conversion of waste polyolefines, *Catalysis Today*, Vol. 65, No. 2-4, 2001, pp. 323-330.
42. Wallmann, P.H.; Thorsness, C.B. and Winter, J.D., Hydrogen production from wastes, *Energy*, Vol. 23, No. 4, 1998, pp. 271-278.
43. Pinto, F.; Franco, C.; Andre, R.N.; Miranda, M.; Gulyurtlu, I. and Cabrita, I., Co-gasification of study of biomass mixed with plastic wastes, *Fuel*, Vol. 81, No. 3, 2002, pp. 291-297.
44. VTT. Power Production from Waste and Biomass IV. In *Proceedings of the VTT Symposium, Finland, April 8-10, 2002*.
45. European Communities, *Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste*; Official Journal of the European Community, L332/91, 2000.
46. Sikalidis, C.; Zabaniotou, A. and Famellos, S., Utilisation of municipal solid wastes for mortar production, *Resources, Conservation and Recycling*, Vol. 36, No. 2, 2002, pp. 155-167.
47. Thipse, S.; Sheng, C.; Booty, M.; Magee, R. and Dreizin, E., Synthetic fuel for imitation of municipal solid waste in experimental studies of waste incineration, *Chemosphere*, Vol. 44, No. 5, 2001, pp. 1071-1077.
48. Tange, L. and Drohmann, D., Environmental issues related to end-of-life options of plastics containing brominated flame retardants; *Fire and Materials*, Vol. 28, No. 5, 2004, pp. 403-410.