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Developments in the End-of-Life management of plastics

A Western European Overview: moving away from disposal

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Prior to this chapter, the IIIEE chapter, I had little to no idea of the complexities and issues surrounding plastics industry. My knowledge in this field has increased tenfold, although there is still a lot more to gain. For introducing me to this topic, the end-of-life management of plastics, a great deal of gratitude is extended to Prof. Thomas Lindhqvist. For supervising my work and their patience throughout, thanks to Dr. Mårten Karlsson and Dr. Andrius Plepys.

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As a final note regarding transitioning up the waste management hierarchy (and writing a thesis) I think Sir Winston Churchill, referring to something completely different, inadvertently summed it up nicely when he said:

> "Every day you may make progress. Every step may be fruitful. Yet there will stretch out before you an ever-lengthening, ever-ascending, ever-improving path. You know you will never get to the end of the journey. But this, so far from discouraging, only adds to the joy and glory of the climb."

Abstract

Plastic materials come in a variety of forms from non-renewable resource based thermosets and thermoplastics to renewable resource based bio-plastics each of which have unique qualities and properties. These materials are seeing ever increasing production and consumption rates throughout Western Europe, being utilized in a growing number of products which inevitably enter the waste stream upon end of life. With waste and resource management attracting a growing amount of attention from all sectors of society there are profound and dynamic developments occurring so as to manage these material resources in a sustainable manner. This thesis attempts to explore developments within the plastics waste management sector from social and environmental issues, political intervention at an EU level, and technological advances in treatment and polymer identification/separation options available and utilized within the Western European geographical region. Specific attention is given to developments and advances in technology both for identifying/separating specific polymer types and in recycling/recovering these material resources. The main drivers, barriers and issues surrounding utilizing this waste resource in a sustainable, environmentally sound and resource efficient manner are discussed in relation to their implications on transitioning up the waste management hierarchy in an integrated system.

Key words: Plastics waste management; bio-polymers; mechanical recycling; feedstock recycling; chemical recycling; recovery options; policy intervention.

Executive Summary

The main goal of this research is to investigate and determine the present condition, developments and trends occurring in the end-of-life management of plastics arising within the Western European geographical region. Furthermore an attempt to identify the drivers, barriers and other factors influencing a move away from direct disposal and aiding a transition up the waste management hierarchy is undertaken.

Two main groups of aspects form the basis of the research and provide the focus in which interviews, literature reviews and the discussion were conducted. These are: Policy, management, environmental and social aspects; and Technology and operational aspects. The results and findings from this process have been utilized to determine where the main developments are taking place, the main barriers and drivers to more sustainable resource use and their implications on transitioning up the waste management hierarchy.

Background

Plastic materials have become an integral part of Western European society and production and consumption continues to rise in all sectors from domestic household through agricultural to industrial applications. The plastics industry is dynamic and is constantly developing new materials and production techniques giving rise to an increasing variety of materials. The major sectors in which plastics are used include packaging applications which, accounting for approximately 37% of the 40 million tonnes of total plastics consumption in 2003, is the largest plastics sector. Building and Construction, and other household/domestic applications account for around 20% of consumption each and the Electrical and Electronic, and Automotive sectors, which are both developing and increasingly utilizing plastics materials, consumed a further 8% each in 2003 (Plastics*Europe*, 2004). The time for which plastic products remain in use varies from as little as 6 months for packaging applications to in excess of 50 years in the building and construction sectors which have direct implications on how design and process developments in production affect the waste management industry.

As a direct and inevitable consequence of increased production and consumption, the generation of plastics waste has grown dramatically in recent years. With increasing attention being given to sustainable resource management, due to environmental and economic considerations, the interest in separately collecting, and recovering plastic materials or energy from these products, has become a predominant issue in the end-of-product-life management sector.

Although being recognised as the plastics waste management option that offers the highest resource saving potential and least environmental impact in a number of instances (i.e. where resources used in collection, separation and recycling are less than or equal to savings made), there are inherent difficulties and limitations associated with the conventional mechanical material recycling of plastics. Due to the incompatibility of different polymer types during melt recycling, the potential for diffusion of additives, pigments and contaminants through out the recyclate resulting in reduced quality of material, and the difficulties in removing such substances from post use materials, the material recycling of post use plastics is complex. One of the most beneficial properties associated with plastics, their low density and weight to volume ratio, which reduces product transportation costs as well as being attractive to consumers, is also one of the major limitations associated with collecting and reclaiming these materials from consumers in an economically efficient manner. Virgin polymers, particularly the widest used commodity polymers (as apposed to engineering polymers), have also traditionally been low cost materials, both making them attractive to producers and at the

same time reducing the financial incentive to recycle them and stimulate market demand for recyclate to make recycling financially viable.

Political intervention

As a result of the increasing volumes of waste arising throughout Europe, and the fact that free market forces alone are not achieving resource use efficiency, a number of policies have been introduced by the European Union pertaining to waste management in recent years. During the fourth European Environmental Action Programme (1987-92) a European Community strategy for waste management was introduced and established the waste management hierarchy as a long term goal for the EU to strive towards indicating options in order of preference with relation to environmental performance and desirability. This hierarchy acts as a guiding principle for EU waste policies, placing avoidance and prevention of waste as the key priority. Thereafter, in descending order of preference and striving towards more efficient resource use the hierarchy prioritises: re-use, recycling, composting, and energy recovery followed by direct disposal, considered to be the least desirable option.

Three product sector specific directives have been produced and adopted within the EU. The first of which, the 1994 Packaging and Packaging Waste Directive, stipulates specific targets for the material recycling of plastic packaging and overall packaging recovery targets. The 2000 End of Life Vehicle (ELV) Directive and 2002 Waste Electrical and Electronic Equipment (WEEE) Directive, although not specifically stating recycling targets for plastic materials, do stipulate recycling rates based on weight of product. As plastics are becoming increasingly utilised within these sectors, plastics recycling and recovery are becoming increasingly important so as to meet recycling and recovery targets. These directives are stimulating and driving further collection and developments in the end of life management of these products.

Other EU waste policies, including the 1996 integrated Pollution Prevention and Control Directive, the 1999 Directive on Landfill of waste and the 2000 Incineration Directive aim at reducing the environmental impact of waste management options. These Directives along with national policies such as introducing landfill taxes are increasing the cost associated with such management options, internalising the associated externalities. Other national policies are stipulating bans and limitations on what waste can be landfilled, all of which are providing incentives for recycling to become more economically attractive management options for a number of plastic waste producing sectors.

Current plastics recycling and recovery trends and issues

Although certain Western European nations have and are limiting the use of landfill, this waste management option remains dominant within the EU as a whole. Although the percentage of plastic material being landfilled has fallen since 1990, the actual weight of plastics being landfilled appears to have continually increased during this same period.

Incineration with energy recovery is the second largest management option utilized within Western Europe as a whole, although issues surrounding emissions, local objection to new incineration establishment and the energy recovery ratio achieved (average throughout Western Europe being ~30%) does affect the development and viability of such facilities. Energy recovery incineration plants do however have an important role to play within a waste management system. Small, light weight and dirty (contaminated) plastics that can not be collected or recovered by other means or which require more resources to collect, separate and recover than is saved, can be recovered within co-mingled waste incineration plants more effectively than by other means.

The findings of this report show that plastic recycling is increasing both domestically and out with Europe, although since 1993 the general volumes being material recycled have merely been keeping pace with increased total plastic waste production. Markets have developed in certain sectors for recyclate materials, especially for agricultural films and industrial packaging materials. However, the main markets, as collected volumes increase and markets are not developing as rapidly, appear to be in Pacific Rim countries, China and India in particular. These are viable markets and can achieve large economies of scale in recycling as post use plastic resources are obtained from several countries and sources, resulting in larger recycling facilities being constructed, and reducing re-processing costs. There are however costs and benefits associated with a reliance upon foreign markets for recycling which are discussed within this report.

The main barriers to increasing mechanical recycling have been identified to include:

- Collected material volumes are increasing however a lack investment in polymer specific identification and separation capacity is limiting the volumes of homogenous post consumer plastics available to domestic recyclers. Combined with fluctuant and volatile virgin and post use polymer prices, and demand from foreign re-processors affecting materials being available at reasonable cost to domestic reprocessors, the establishment of viable domestic markets within Western Europe is proving difficult for some polymers and waste streams.
- Health and safety issues related to recyclate utilized in food contact packaging (the largest plastics waste material producing sector) as well as other quality aspects including colour, melt flow characteristic changes, additives that give rise to concern in recyclate and other technical limitations including heat and shear degradation restricting melt re-processing to approximately nine cycles do affect market development. A lack of sufficient, economical and recognised quality standards and testing procedures for recycled materials is also preventing the further market development of recycled plastics within the Western European plastic product industries;
- Collection infrastructure and public/industry participation in recycling remain limited in certain regions;
- Knowledge transfer and diffusion between all actors in product life cycles is lacking resulting in a disconnection between recyclers and product manufacturers where recyclate could be utilized.

Some of these barriers are being overcome through technology developments however others require to be addressed from an organisation level. Identified drivers to material recycling include:

- Recent increases in fossil mineral prices, due to increased demand and issues affecting supply, have resulted in improving the economics (due to higher prices paid for recyclate) and market demand for recycled materials;
- Policy intervention as previously introduced is driving collection rates and increasing the costs of less desirable alternatives making recycling financially more attractive. Political and industry commitments to phasing out detrimental additives from plastics and specific products are also aiding developments in materials that are capable of being effectively recycled.

- International cooperation can aid and achieve economies of scale and cost reductions for: separation (i.e. separation taking place in low cost nations, or by automated separation within Europe at a number of centralized locations (e.g. the Norwegian-Danish cooperation)); and recycling through large scale recycling in globally centralized locations such as India and China. However there are inherent issues with relying upon low cost nation capacity.

Technology developments

A number of important developments are taking place within the plastics waste management technology sector which is enabling and driving further recycling/recovery rates. Automated identification and separation technologies are increasingly entering into commercial operation within the Municipal plastics waste collection systems and for WEEE and ELV plastics and shredder residue resulting in increased volumes of homogenous, higher quality materials being reclaimed from the various waste streams.

Recent developments and investments in mechanical recycling techniques for recycling Polyethylene Terephthalate (PET) packaging materials have enabled previous barriers associated with the closed loop recycling of polymers which come in direct contact with foodstuffs to be overcome. This barrier to closed loop food stuff packaging is that polymers commonly interact with chemicals in which they come in contact with. The diffusion of these chemical substances into and in turn out off plastics causes concern for the application of recycled materials in foodstuff packaging as the potential for contaminants to enter the material throughout the previous life cycle and during reprocessing is high which in turn may later enter the foodstuff contained within the new packaging material. Research into developing techniques and processes for recycling other polymers (particularly HDPE) suitable for food contact applications is being undertaken at present and is likely to aid further closed loop recycling of packaging products in the future.

Advanced recovery options, including feedstock and chemical recycling which use thermal or chemical processes to depolymerise plastics to their original constituent substances which can thereafter be repolymerised to produce new plastics or used for other applications, are also developing. Having seen an initial commercialization period in the early 90's within Germany following the introduction of the German packaging ordinance, which, due to the volumes of materials reclaimed from the waste stream, and the immature stage and limitations associated with mechanical recycling, such processes have gone through a period of stagnation and reduced use since the mid 90's. Advanced recovery options are now seeing revived interest and development with chemical recycling of Polyamide being undertaken within Germany, chemical recycling of PET developing within Italy and Feedstock recycling processes to produce synthetic Diesel fuel emerging in a number of European countries.

Small scale pyrolysis plants for producing synthetic diesel from thermoplastics which are too contaminated or otherwise unsuitable for mechanical recycling, although yet to be fully established within Europe, may result in an economically viable outlet for residual plastic materials remaining after separation for higher quality materials has been performed. This may encourage increased collection and separation as these processes appear to be cost competitive with alternative processes such as landfill and incineration. Such developments are important in regions where large scale incineration capacity or alternative recovery options are not available due to high capital investment and development costs.

Trials are also being undertaken to chemically recycle PVC in Denmark, although the high cost associated with this process, leading to high gate charges and as a result lack of materials, technology development issues, and anticipated legislation stipulating PVC specific recycling targets not coming into force as yet, are affecting the viability of this process.

There are barriers to the wider development, establishment and adoption of advanced recovery options. Inherent risks associated with investment exist, particularly in relation to price volatility of virgin and post consumer materials. Securing supply and critical mass of post consumer materials at appropriate price to cover investment costs can also be an associated limiting factor, especially where processes are reliant upon plastics (homogenous or mixed) materials exclusively. High energy and process costs also make advanced recycling methods unfavourable at present. Although advanced recycling methods are attractive options and have been heralded as having great potential in the plastics recycling industry, economics (cost competitiveness with alternatives) remain the limiting factor and main barrier to further investment and polymer to polymer advanced recycling systems are likely to remain in limited commercial use until such a time as virgin feedstock materials increase substantially in price and remain high compared to traditional cost over a prolonged period.

Bio-polymers (plastics constructed from renewable raw materials) are penetrating into the petrochemical polymer dominated market in increasing quantities and applications, offering significant energy savings over the use of petrochemical based polymers. Production capacity developments are enabling economies of scale in bio-polymer production to be achieved, reducing their costs. At the same time the increasing price of conventional petrochemical based plastics and attention being paid to finite fossil mineral resource, are making bio-polymers competitive with conventional polymers and thus are becoming increasingly attractive to various sectors. Packaging and agricultural films are the main sectors which bio-plastics shall likely become common place over the coming years. If these materials are to enter into the market further, effective means for which to reclaim them from the waste stream and treat them are required to be developed so as not to inhibit conventional plastics recycling (if bio-plastics are recycled along with conventional plastics, material degradation occurs). Composting, combustion and other thermal treatments such as gasification are increasingly becoming available which can treat such polymer types, however automated polymer separation equipment maybe required in order to identify and separate them from conventional plastic products.

It is apparent that no one solution exists to make full use of post use plastic material resources from an environmental or financial view point. Therefore an integrated resource management system, incorporating the various management options available and developing, should be adopted in order to achieve the greatest environmental and economic gain. This allows for the various, waste streams, demographic, geographical and socio-economic and political conditions that are found across Europe to select the post use plastics management options which are optimal for any specific region and waste stream produced. This shall enable a transition away from dependence on landfill and up the waste management hierarchy whilst making optimal use of post use plastic resources.

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List of abbreviations and acronyms

APME -	Association of Plastics Manufacturers Europe (now Plastics*Europe*)
APPE -	Association of Petrochemical Producers in Europe
ART -	Advanced Recovery [Recycling] Technologies
ASR -	Automotive Shredder Residue
BDP -	Biodegradable Polymer
DSD -	Duales System Deutschland
EfW -	Energy from Waste
ELV -	End of Life Vehicles
EPR -	Extended Producer Responsibility
EU -	European Union
GBP (£) -	Great British Pounds (Sterling)
IBAW -	The international industry platform for bio-plastics & biodegradable polymers
IPPC -	Integrated Pollution Prevention and Control [EU Directive]
LIBS -	Laser-induced Breakdown Spectroscopy
MBT/BMT -	Mechanical Biological Treatment/ Biological Mechanical Treatment
MPW -	Mixed Plastic Waste
MRF -	Material Recovery Facility
MSW -	Municipal Solid Waste
NIR -	Near Infra-Red
OECD -	Organisation for Economic Co-operation and Development
PMB -	Plastic bottle, Metal packaging and Beverage cartons
PRO -	Producer Responsibility Organisation
PRN/PREN -	Packaging Recovery Note/ Packaging Recovery Export Note
PRS -	PET Recycling Switzerland
R&D -	Research and Development
RDF -	Refuse Derived Fuel
RRM -	Renewable Raw Material
SPI -	The Society of the Plastics Industry in America (USA)
SRF -	Solid Recovered Fuel
SVZ -	Sekundärrohstoff-Verwertungs-Zentrum Schwarze Pumpe [feedstock recycling plant, Germany]
TFS -	Transfrontier Shipment Regulations
WEEE -	Waste Electrical and Electronic Equipment
WFD -	Waste framework Directive
XRF -	X-ray Fluorescence

Major commodity plastics

HDPE –	High Density Polyethylene
LDPE –	Low Density Polyethylene
LLDPE –	Linear Low Density Polyethylene
PE -	Polyethylene
PET/ PETE -	Polyethylene Terephthalate
PP –	Polypropylene
PS –	Polystyrene
PVC –	Polyvinylchloride
V -	Vinyl

Engineering and other plastics

ABS -	Acrylonitrile Butadiene Styrene
ASA -	Acrylicester Styrene Acrylonitrile
EVA -	Ethylene vinyl acetate
EVOH -	Ethylene vinly alcohol
HIPS -	High impact polystyrene
PBT -	Polybutylene terephthalate
PC -	Polycarbonate
PMMA -	Polymethyl methacrylate (Acrylic)
PTFE	Polytetrafluoroethylene
SAN -	Styrene Acrylonitrile
TPE	Thermoplastic elastomer
TPR	Thermoplastic rubber
TPU	Thermoplastic polyurethane
TPO	Thermoplastic olefin

Bio-polymer plastics

PLA –	Polylactic Acid
PHA –	Polyhydroxyalkanoates
CA -	Cellulose acetate

Monetary conversion rate: £1 = €1.48 / €1 = £0.68 as of August 2005

1. Introduction

Increasing volumes of manufactured polymers for use in an expanding global plastics market has placed substantial pressure on finite natural resources. The world's annual consumption of synthetic polymer plastics produced from non-renewable petrochemical feedstock has continually increased year on year from around 5 million tonnes in the mid 1950's to almost 100 million tonnes today (Waste Watch, 2004). This growth can partly be attributed to the development of new polymer design characteristics providing more durable, lighter weight and stronger plastics which withstand deterioration (i.e. photo-degradation, hydrolysis, oxidation, biodegradation, shock loading/impact etc.) to a far higher degree than previous polymer types and applications in the past. This allows for extended product life and plastics proving a favourable alternative to other traditional materials such as metals and glass (Albertsson and Huang, 1995).

However, the consequences of recent (particularly 2003 to 2005) global environmental and geopolitical events including the instability within the Middle Eastern oil producing regions, and hurricane Katrina that ravished the oil refining installations on the South Eastern coast of the USA causing global oil prices to hit record highs (BBC, 2005) has highlighted the disadvantages of a dependence on finite crude oil resources. These and related similar past events (e.g. the 1972 oil crisis) having lead to, and combined with, increased attention and recognition of the concept of sustainable development (incorporating waste management and other global environmental issues including green-house-gases, toxic, hazardous, and other detrimental substances released throughout the life of products), contribute to the requirement and need to move away from direct disposal of plastics 'waste' and strive towards more sustainable 'resource' management. This requires to be approached from all stages of the entire life cycle of the products which we as a society produce, consume and discard. Although plastics materials based on renewable raw materials are entering the market in increasing volumes, there remain issues associated with the development and use of these materials which must also be managed in an environmentally acceptable and sustainable manner.

At present waste and resource management is attracting substantial amounts of attention from governmental authorities at all levels from international, through national to regional and local authority. The OECD, in 2001, set a goal of decoupling environmental pressures from economic growth. Since then, an investigation into the potential of different approaches to "sustainable materials management" based upon material flow accounts, has also been initiated. In 2002, the countries involved in the World Summit on Sustainable Development agreed to address unsustainable production and consumption practices. This is aimed at decoupling economic growth from environmental degradation by improving the way in which society utilize resources and production processes through more efficient and sustainable practices thereby reducing resource degradation, pollution and waste (COM, 2005). Industry is being pushed by governmental legislation as well as from an increasingly environmentally conscious general public putting consumer demands on all aspects of industry from manufacturers to retailers. Industry has also become more conscious of a responsibility to lesson impact on the natural environment and is creating voluntary and self initiated programmes to strive towards more sustainable consumption and production throughout the entire life cycle of polymer products.

The European Union is driving a harmonized effort in political intervention by introducing environmental Legislation, Directives and Regulations aimed at waste treatment facilities and specific waste streams. These policies are having impacts at all levels of the community from national to local level as well as further afield. Having identified priority waste streams, EU policy is developing dynamically and incorporating the polluter pays principle through producer responsibility in order to establish a more integrated system. This exerts pressure on a larger number of actors involved in the product life cycle to take responsibility for the products they produce, sell, consume and discard than previously practised. The waste management hierarchy, introduced within the 1987 European Community strategy for waste management, acts as a guiding principle for these policies placing avoidance and prevention of waste as the key priority. Thereafter, in descending order of preference and striving towards waste minimisation; re-use, recycling, composting, and energy recovery followed by direct disposal, considered to be the least desirable option.

Although efforts have been made to reverse the trend in increased production and consumption of waste by reducing, minimising and reusing the resources and materials society utilizes, there is at present and for the foreseeable future a substantial and increasing amount of post use and scrap plastic material entering the waste management system. Once discarded, the products and materials require to be managed in some form. A number of options are available for the end of life management of plastics however all have various degrees of technical limitations, costs and benefits. EU policy places increasing demands on the collection of materials and products, at the same time promoting the concepts of the waste management hierarchy. This indicates a long term vision and goal of a more sustainable waste management system and breaking the link between economic growth and waste arisings, a trend seen in many if not most OECD countries today. A gap exists between this vision and goal and the actual conditions today, indicating there is considerable room for progress.

1.1 Purpose, Aim and Research Questions

Dynamic movements are taking place throughout the entire life cycle of plastic products with various technologies, legislation, demands and initiatives being trialled, introduced, adopted and applied. With such movements occurring within a number of societal sectors it is often unclear what exactly is happening within the plastics sector. The purpose of this research is to highlight the problems associated with plastics production, consumption and waste management activities and the developments taking place in these sectors. Further more the aim includes identifying the vision and goal of the European Union, the gaps that exist between this vision and present conditions, and the drivers and barriers that lie behind more sustainable management of this material resource and to determine how we as a society can best deal with this material arising.

In order to achieve this desired purpose the following research questions are posed:

RQ1. *What technologies are currently available and on what scale are they being utilized within Western Europe for the recovery and recycling of plastics waste?*

RQ2. *What developments are taking place and what are the identifiable drivers and barriers to establishing further plastics recycling and recovery within the Western European geographical region?*

RQ3. *What are the implications of the identified developments, drivers and barriers on plastics waste management in Europe moving away from disposal and how can these enable, or be overcome to aid, a transition up the waste management hierarchy?*

1.2 Scope and limitations

This study focuses on the common thermoplastic, themoset and biopolymer plastic materials (as defined in chapter 2) utilized in products including packaging, electrical and electronic equipment, construction, industry, agriculture and other household goods. Elastomers and textiles are excluded from the study as these can be referred to as 'non-plastic polymers' due to the fact that they serve distinctly separate functions from those of thermoplastics and thermosets. It is evident that waste minimisation, reduction and reuse are important preventative operations; they are ultimate goals and therefore located at the top of the waste management hierarchy. Equally important however, is how we have and shall continue to sustainably deal with the unavoidable waste produced by society, this paper is therefore focused on important concepts at the lower levels of the hierarchy.

The Western European geographical area, incorporating the fifteen European Union nations (EU15, prior to the EU expansion in 2004) and the European Economic Agreement nations of Norway and Switzerland (EU15 +2) is the focal region. A general Western European overview is portrayed in order to provide a holistic overview of this region's activities, developments and their implications on the EU stipulated requirements for plastics waste and resource management activities.

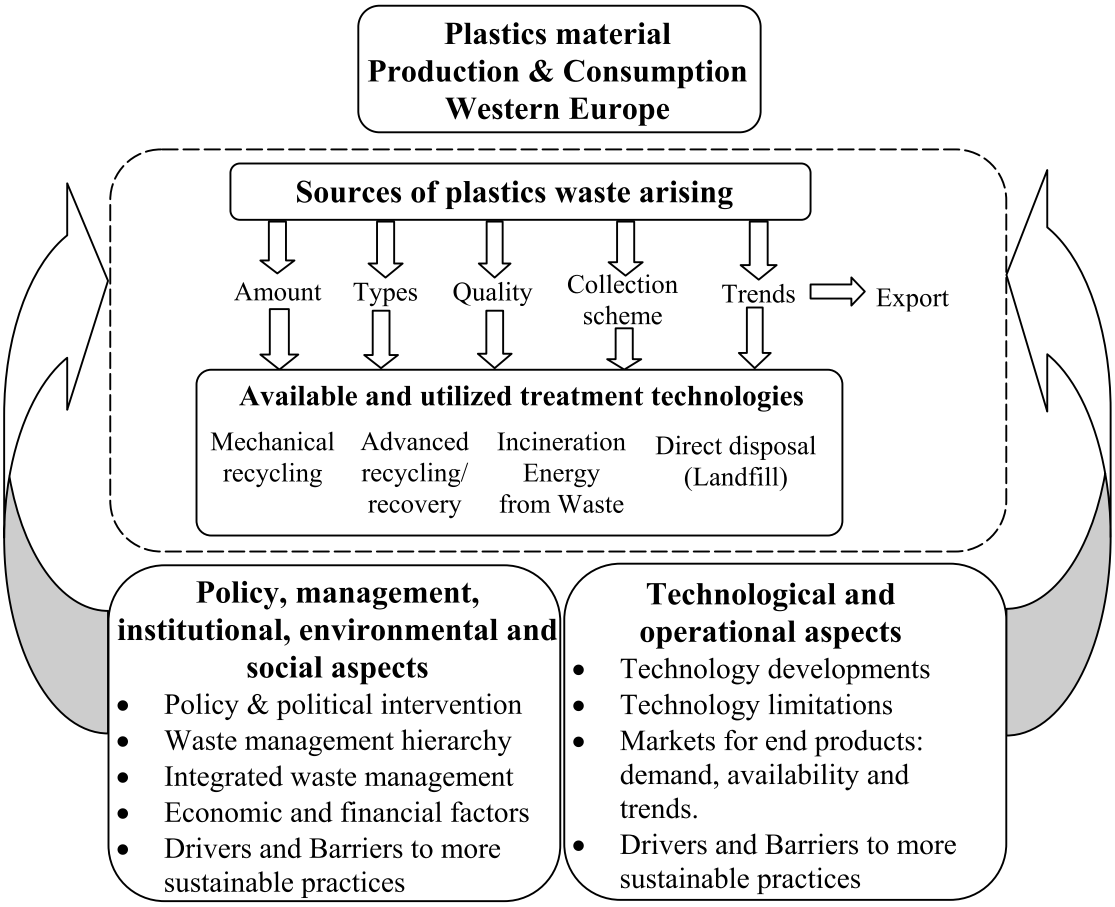

Figure 1: General overview and scope of research area

Figure 1 provides an illustrative overview of the study area and issues incorporated into the thesis scope. Plastics material production and consumption within Western Europe is an introduction and provides the opportunity to outline the complexity of this material. This is followed by a description of applications for which they are utilized which inevitably results in waste generation at the end of the intended product life. The processes and activities presented within the dotted box illustrate the main focus area of the research coupled with an analysis of policy, management, institutional, environmental and social influences alongside technological and operational interactions that ultimately influence and affect the system. These aspects are reflected upon so as to determine the extent to which these two key areas influence how Western European society can deal with increased plastics waste arising.

Degradable and Biodegradable polymers, which are entering the market place in increasing volumes, shall be introduced in order to provide insight in to developments of materials that offer an alternative waste management option and have associated implications on production, collection, separation and recycling activities within the wider plastic product family.

Limitations

Language barriers along with a large number of stakeholders contacted being unavailable for comment has lead to some information gaps in certain countries and sectors.

Available data on production, consumption and waste arising, how they are treated, and opinions on direction and conditions are often influenced by vested interest groups whether industrial, environmental groups, politically orientated or socially orientated to public opinion or perceptions. This has resulted in some difficulties in compiling objective, real data on today's and past actual conditions and trends. However a number of sources were reviewed in order to obtain and present a balanced review of opinions and data.

It is appreciated that there are many factors that influence and determine the waste management options utilized within a wide geographical context such as Western Europe. Differences in managerial responsibilities within individual municipalities and local level political, social and other factors all contribute to the complexity and issues surrounding waste management. However this thesis concentrates primarily on where the waste is arising on a Western European level, the European Wide political infrastructure, social aspects, environmental and other generic issues that impacts activities in the region as a whole. Technological issues have been looked into on an individual facility level for advanced recycling/recovery technologies where as mechanical recycling, energy from waste incineration and landfill have primarily been taken from a wider regional level.

Although effort has been made to include the main advanced (feedstock and chemical) recycling facilities and provide detail on new developments taking place, there will inevitably be a number that have not been covered. This thesis does however provide an overview of the general situation and the main technological developments determined to be taking place by the author and interviewees.

1.3 Methodology

In order to achieve the desired aim and objectives set out within this research area and answer the research questions posed a number of actions were taken to obtain an overview of the current trends and developments influencing this material sector. The following provides a breakdown of the methods utilized.

1.3.1 Framework

Two main groups of aspects were identified within literature relating to plastics waste management (illustrated in figure 1, section 1.2). These two main aspects form the basis of the research and provide the focus in which interviews, research and the discussion were conducted.

1. Policy, management, environmental and social aspects

This group of aspects is largely based on socio-economic and socio-political issues which influence the way in which society as a whole perceive and addresses plastics product life cycle management issues. The issues lying within this main aspect are reviewed in order to obtain insight into the direction, vision and goal that end-of-life management of plastics is and should be taking in order to make maximum use of the resources.

Political intervention and policies (directives, regulations and programmes) pertinent to plastics resource management emanating from the European Union were reviewed in order to identify where the EU priorities lie and actions are taking place. The waste management hierarchy has been used as a guiding framework for action. Relevant literature (Life Cycle Assessments etc) was reviewed to determine whether the hierarchy stands true, thereafter each main option within the hierarchy was reviewed in order to identify how each recovery and recycling option can be utilized and the limitations to each. With the hierarchy as a guiding framework, the concept of integrated waste management was reviewed so as to determine how various factors such as social, economic and technology influence which treatment option is utilized and the barriers and drivers to the use of each treatment type based on each of there factors.

2. Technological and operational aspects

Technology and operational aspects are separated from social issues as these are largely developed and enter into use as a result of the way in which society is directing actions and attention as well as being independently developed through industry R&D. A review of the current developments in technology, innovation and operational activities including, collection, separation, recycling and recovery was conducted and their interrelation and implications in relation to policy and social aspects as described above were made.

For each technology identified, the technical process was reviewed in order to ascertain how they differ from one another, their technical and market status and economic viability, the resource use and benefit of each technology, their place within an integrated waste management system, their position within the waste hierarchy and implications on transitioning up it. From this review the limitations and benefit of each technology were ascertained and linked with the wider picture by determining the interrelation between each technology and the issues identified within the previous main aspect presented in point 1 above.

1.3.2 Data Sources

1. Literature review on plastics, waste management options, and EU waste policy

In order to identify and outline the main issues surrounding plastic material resources a review of the production and composition of both petrochemical (non-renewable raw material) and biological (renewable raw material) was conducted from relevant literature, industry group reports and online news articles from both media and industry. Primary data in the form of EU directives and eurostat statistics were reviewed so as to identify the relevant policies relating to plastics waste management and general trends occurring. Literature pertaining to plastic waste management options and concepts, including landfilling, recycling, recovery, integrated waste management and the waste hierarchy has been reviewed so as to provide details on technical limitations and other relevant issues surrounding these practices.

2. **Study on commercially operational and developing waste management facilities and issues surrounding management practices**

Primary and secondary data in the form of industry body, EU, and interest group reports, technical publications, conference proceedings and World Wide Web internet sites* were reviewed in order to compile information regarding currently operational, utilized, and emerging technologies for dealing with plastic waste resources as well as those in the development stage.

3. **Interviews with various actors throughout plastics material life cycles**

Recycling and plastic product processors in Sweden and Denmark were initially contacted to provide an indication of the issues surrounding the topic. Having identified a number of relevant areas of interest from these contacts further literature was studied to build more in-depth knowledge into these and other issues prior to revisiting the interviewees. Further contacts throughout Europe based on issues arising from both internet searches, initial contacts (via the 'snow ball' contact method) and through relevant companies appearing in Rapra technology's "European Plastics and Rubber Directory, 2004-2005" were also made and interviewed.

Interviews were carried out with a number of actors within the plastics manufacturing and waste management sector. These included: Producer Responsibility Organisations; Recycling/recovery companies; Collection companies; Plastic processors; Bio-plastic groups; and other related organisations (a full breakdown of the actors interviewed is provided within Appendix 1).

1.3.3 Discussion on findings

Based on the issues arising from literature, EU policy intervention and the findings from interviews the main identified issues are discussed in relation to the two main aspects outlined in section 1.3.1 (illustrated in figure 1 section 1.2). The implications of the findings on developments, trends, barriers and drivers towards more sustainable plastic resource management in relation to the waste hierarchy and the concept of integrated waste management form the main emphasis of the discussion. Each main treatment option group is reviewed independently whilst referring to the interrelationship of each.

1.4 Thesis outline

Chapter 1: Introduction presents the problem definition and justification for this research as well as developing the research questions and laying down the scope, limitations and methodology utilized in compiling this thesis work.

Chapter 2: Plastics in Western Europe introduces plastics and trends in production and consumption of both petrochemical and renewable raw material based plastics. The properties

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* Internet searches were performed through the use of Lund Universities LOVISA (Library catalogue of Lund University libraries), ENDS (Environmental Data Services) search option (www.endsreport.com), EU web site, and google and search engine facilities.

and problems associated with certain plastic materials are provided in order to present an overview of this material resource.

Chapter 3: Sources of plastics waste with plastics being utilized in a diverse range of consumer goods and manufactured products there are a number of issues surrounding the reclamation of material from the various waste streams from which they arise. This chapter aims to present what plastic types are utilized and enter the waste stream from different applications and products, the trends associated with these consumption practices and challenges for the end-of-life management relating to these product types.

Chapter 4: Plastics waste disposal and treatment options provides a general introduction to the waste management treatment options available so as to illustrate their limitations, costs, benefits, and the complexity of dealing with such a wide variety of materials. Justification of the waste hierarchy and integrated waste management is also introduced within this section

Chapter 5: European Union policy intervention, a general overview of how the European Union envision waste management activities should be practiced and the policy intervention that has taken place attempting to influence a more sustainable resource management system shall be presented..

Chapter 6: Current Western European situation aims to present the current Western European situation with regards to how plastics waste are collected and treated from the various waste streams introduced in chapter 3 and provide a more detailed description of the developments and trends associated with these activities on a Western European wide basis. This section is largely based on literature available on the developments taking place and interviews with relevant key actors within industry and attempts to provide an answer to the first and partially the second research question.

Chapter 7: discussion takes the concepts of sustainable waste management focusing on the waste hierarchy and integrated waste management including issues arising from the findings presented in chapter 6. Information provided in previous chapters is discussed in order to determine how the developments, drivers and barriers influence the establishment of further recycling in Western Europe and furthermore, answer the third research question.

Chapter 8: Conclusions and recommendations presents summarised answers to the three research questions and highlights the key issues surrounding plastics waste management in Western Europe as well as providing recommendations on how a transition up the waste hierarchy may develop and be promoted. Recommendations for further research are also detailed within this section.

2. Plastics in Western Europe

This chapter aims to introduce plastics materials available including chemosynthetic and renewable raw material based polymers, trends within Western Europe with regards to polymer production and consumption, with the overriding aim to provide insight into the material and product properties of plastics and the implications these have on the options available for their end of life management.

2.1 Conventional synthetic plastic polymers

Plastics is a broad term which covers a wide range of organic materials consisting of a sequence of monomer chains forming polymers exhibiting "plastic" properties (i.e. the ability to flow and mould into a desired shape when heat and or pressure are applied and retain that shape once these forces are removed) (Hocking, 1998). The most abundantly utilized plastic polymers (also referred to as resins) are chemosynthetic polymers (referring to industrial production from chemicals (i.e. petrochemical derived hydrocarbons) under controlled conditions) which are constructed from repeats of monomer units derived from petroleum and to lesser degrees Natural gas and coal and utilized on a large scale for consumer goods. Although the structure of a polymer can contain many different elements, the basic building block is essentially the same, being based on a backbone of carbon as their main structure for which crude oil derivatives are well suited due to its hydrocarbon structure, low cost and relatively high abundance (Athalye, 1995, p3). Within this basic building block, the structural arrangement and average length of the polymer chain, the types of monomers utilized, and material additives all give plastics their properties allowing for a great variety of materials and versatility (EIPPCB, 2005).

Since the introduction of plastic materials into the market place, synthetic polymers have received an ever increasing demand and development process with some fifty different plastic groups now existing, incorporating hundreds of different varieties and blends, and many more specific compositions and properties all of which have individual characteristics (Waste Watch, 2004). However, within this wide range of materials available, there are certain similarities which exist and thus the plastics field can be broken down and classified into two distinct basic types based upon behavioural patterns and response to heat and pressure, which in turn is important for the recycling route available for the materials[†] (Athalye, 1995, p3):

1. *Thermoplastic* – consist of linear or branched chain polymers that can generally soften, flow and can be remoulded by the application of heat and pressure a given number of times without appreciable loss in physical properties (e.g. Polystyrene, Polyethylene, Polyvinyl Chloride, and Engineering plastics such as ABS and Polycarbonates etc.)

2. *Thermosetting* – consist of highly cross linked polymer chains that hardened in the mould in which they are to take the initial shape off and cannot be re-softened or reformed through the application of heat and pressure after hardening (e.g. Phenol Formaldehyde, Unsaturated Polyester and Epoxies etc.)

Plastics exhibit a range of properties and combinations thereof that make them attractive to designers and product manufacturers alike, these include being: flexible or rigid, transparent or opaque, hard or soft, and resistant to environmental conditions or degradable. Other benefits that polymers can bring to various applications are: their ability to reduce the weight of a given

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[†] a third type also exists, elastomers, which are beyond the scope of this study

product and thereby reduce transportation and fuel costs; their ease of processing into a variety of shapes; provide electrical insulating properties to electrical and electronic applications; ability to produce aseptic containers; resist corrosion, chemical degradation, mold etc which all contribute to their increasing usage (EIPPCB, 2005). Further detail on specific technical compositions and characteristics of polymers and plastic properties are provided in appendix 2. Applications for different plastics can vary substantially from polymer type to type. Table 1 provides a brief overview of the major thermoplastics and thermosets types and their primary applications.

Table 1: Major plastic types and primary applications (PlasticsEurope, 2004)

Thermoplastic/ thermoset	**Plastic/ Polymer type**	**Primary application**
Major Thermoplastics	Low Density Polyethylene (LDPE)	Injection mouldings e.g. food trays; Extrusions e.g. pipes and guttering, plastic bags, toys, coatings.
	Linear Low Density Polyethylene (LLDPE)	Carrier bags and films
	High Density Polyethylene (HDPE)	Blow moulded containers, milk bottles, toys, housewares, gas pipes, industrial wrappings and film.
	Polypropylene (PP)	Film, battery cases, microwave-proof containers, crates, automotive parts, electrical components, yogurt cartons, textile applications e.g. carpets, ropes.
	Polyvinyl Chloride (PVC)	Window frames, pipes, flooring, wallpaper, bottles, cling-film, toys, guttering, cable insulation, bank machine cards, medical products.
	Polystyrene (PS & EPS)	Electrical appliances, thermal insulation, tape cassettes, cups, plates, toys, meat trays.
	Polyethylene terephthalate (PET)	Soft drink and water bottles, textile fibres, film food packaging.
	Styrene Copolymers (ABS/SAN)	General appliance mouldings.
	Polymethylmethacrylate (PMMA) a.k.a. Acrylic	Transparent all weather sheeting, electrical insulators, bathroom units, automotive parts.
	Polyamides (PA) e.g. Nylon	Films for packaging of foods such as oils, cheese and boil-in-the-bag products, for high temperature engineering applications and textile fibres.
Major Thermosets	Phenolics	Adhesives, automotive parts, electrical components.
	Epoxy resins	Adhesives, automotive components, E&E components, sports equipment, boat hulls.
	Polyurethanes (PU)	Coatings, finishes, cushions, mattresses, vehicle seats.

Additives are an important constituent of most plastic resins, and are also have important implications in terms of waste management options as various elements and chemicals utilized within materials which influence the end of life treatment technique available. Practically all manufactured plastics, whether thermoset or thermoplastic, polymer blends or single polymers, utilize a variety of additives to enhance their properties, meet performance requirements and/or the processing capabilities and allow for a variety of applications for one plastic type (Brody and Marsh, 1997. p8). Additives include antioxidants, UV stabilizers, flame retardants, heat stabilizers etc., pigments, and fillers such as talc, calcium carbonate, silica and glass fibres, and natural fibres from flax and hemp etc. can be added to reduce costs and improve rigidity (Brody and Marsh, 1997. p8; Athalye, 1995, p4). A number of these additives can be toxic however; lead, cadmium, mercury and hexavalent chromium have been used in plastic manufacturing in inks, dyes, pigments, adhesives, stabilizers, and other additives.

Although some of these toxic additives have been banned from some plastic products in certain countries they still, controversially, continue to be utilized by manufacturers (Brody and Marsh, 1997. p354; McDonough and Braungart, 2002. p5; Greenpeace, 1999). Along with these heavy metals, other potentially toxic or harmful substances may exist, one particular case is phthalates used as a plasticiser in flexible PVC which are suspected of causing cancer and having endocrine disrupting properties (McDonough and Braungart, 2002. p5). The actual polymer content of a plastic material can vary substantially from as little as 20% to 100% by volume depending on the amount and type of additives utilized (Goodship, 2001).

The environmental impact from polymer manufacturing varies between production facilities and polymer type produced. For example the production of Polyurethane utilizes hazardous isocyanates as intermediates, styrene in PS is also known to be toxic, and brominated flame retardants utilized in electronic appliances released in production and end-of-life are also of concern (Greenpeace, 1999). Within the general area of the synthetic polymer industry it is estimated that the consumption of mineral oil utilized for the production of plastics equates to around 8% of the total annual global mineral oil extraction and production, 4% of which is utilized as feedstock (i.e. as the building block in polymer construction) and a further 4% during the plastics manufacturing processes (i.e. for energy production within the processing stages) (BPF, 2005). As an example of the petrochemical products utilized in plastics material production, in order to produce 1kg of PET or LDPE, 80MJ energy equivalents are required. This equates to approximately 2kg of crude oil, 1kg (or 40MJ) utilized as the feedstock raw material for production (retained within the plastic material) and 1kg (the other 40MJ) being combusted in order to produce the material (Mecking, 2004; Boustead 2001). Synthetic polymer manufacturing therefore contributes to the depletion of non-renewable resources and extraction, transportation and manufacturing activities contribute to air, water and soil contamination from emissions and spillages.

2.2 Degradable and Biodegradable plastic polymers

Biodegradable and degradable polymers (which have distinctly different characteristics) offer an alternative to traditional synthetic polymers (which generally exhibit long life properties and remain intact until managed within specific waste management treatment technologies such as thermal or mechanical treatment).

Biodegradable polymers (BDPs) cover a broad range of polymer materials that exhibit the ability to naturally degrade by biological activity under specific environmental conditions to a defined extent and within a given time. Plastics can be synthetically manufactured from fossil material feedstock's such as petroleum as previously discussed, they can be produced from biological sources (also referred to as renewable raw materials (RRM) such as maize, potato, wheat and other carbohydrate sources as feedstock), or through a combination or blend of both feedstock sources and various additives (Murphy and Bartle, 2004).

Being sourced from biological feedstock (biopolymers) does not necessarily provide polymers with an ability to biodegrade in such a manner so as to be classed BDPs and the properties that enable polymers to undergo degradation from micro-organisms such as bacteria and fungi are not solely dependent on their biological origin either. This is dependent upon the chemical and physical structure (in particular the molecular weight, type of chemical bond in the polymer, and on the properties of the monomer) composition, processing techniques and additives incorporated into the plastics material which can either promote or inhibit biodegradation (Albertsson and Huang, 1995). Both conventional synthetic polymers and biopolymers can be constructed in such a way so as to provide the plastics material with these properties. Traditionally synthetic petrochemical-derived plastics are enhanced with additives to prevent environmental degradation taking place thereby prolonging the usable life of the materials. Research carried out in the 70's centred on capturing the degradable qualities existing in these materials to enable degradation after a certain period of time primarily in response to declining void space in landfill. However the research was thwarted by difficulties in producing a plastic that would not degrade too early (i.e. whilst still in use) as well as materials that only partially degraded and those that left toxic substances after degradation took place (Hulse, 2000). The development of BDPs has also been hindered by high development costs, competition with the material properties and lower cost of conventional plastics, and a lack of acceptance by producers and consumers alike (Omnexus, 2005).

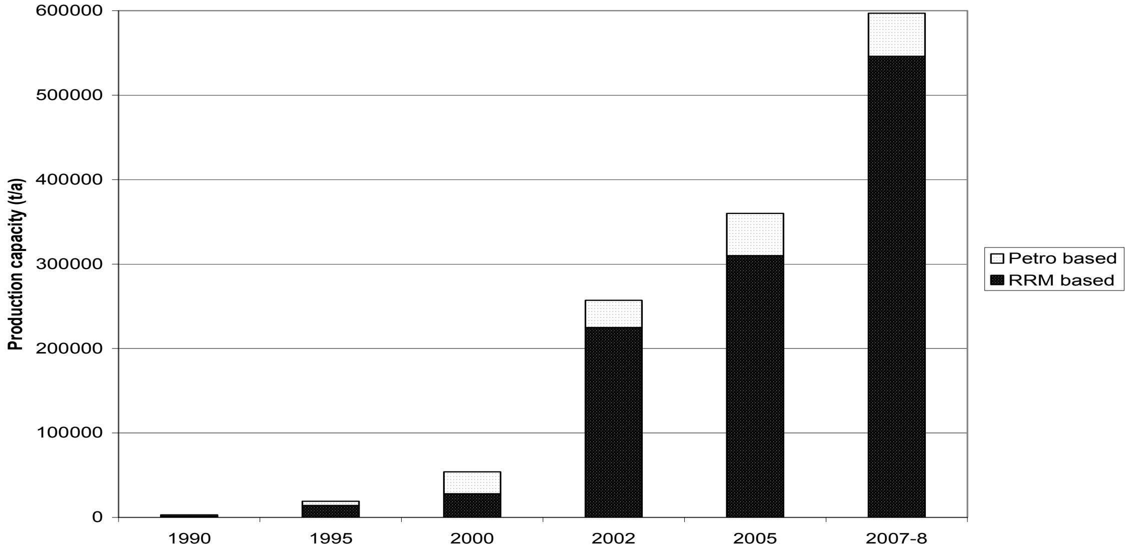

Figure 2: Past and present global production capacity of biodegradable polymers including future predictions. (Source: IBAW, 2005).

Interest in RRM based polymers in the 70's was primarily a result of the 1973 oil crisis and the realisation that supply of fossil oil feedstock was not secure, however, after oil prices fell it was no longer such an issue (Mecking, 2004). Lately this interest has been renewed and attention drawn to the disadvantages of overdependence on finite fossil resources, a transition induced by unstable geopolitical influences on oil supply and the growing awareness of anthropogenic climate forcing. This has prompted demand for more sustainable production and consumption practices through EU legislation, consumer awareness of environmental issues and advances in technology, such pressure to create BDPs has caused world production capacity to increase substantially over the past decade (figure 2) (Mecking, 2004; IBAW, 2005).

RRM based biopolymers represent the highest proportion of truly biodegradable production capacity as illustrated in figure 2 which is anticipated to continually grow over the coming years as technology develops and larger production facilities take advantage of economies of scale resulting in lower production costs. Within Western Europe consumption of bio-plastics in 2004 has been estimated to be in the region of 40 thousand tonnes having grown from 8 thousand tonnes in 2000 (Schnarr, pers com, 2005) with the world market for bio-plastics (RRM based) by 2020 being estimated to reach 30 Million tonnes (ENDS, 2004a) although this shall still only represent an estimated 2% of the total plastics production (Murphy & Bartle, 2004). Presently the main developments in RRM based biopolymers are in the production of polylactic acids (PLAs) produced by the fermentation of carbohydrates, and polyhydroxyalkanoates (PHAs) which are produced naturally by various bacteria (Appendix 7 provides a breakdown of the main biodegradable polymer types, feedstock source and characteristic properties) (Mecking, 2004; Narayan, 2004; Omnexus, 2005).

In terms of energy consumption in the form of fossil fuel equivalents required for the production of biopolymers, in the case of PLA production, around 57MJ is consumed by the production of fertilizers, pesticides, transport of raw materials and in process energy for polymer production in order to create 1kg of PLA. This energy primarily comes from the combustion of fossil fuels at present and although carbon sequestration during the growing of plant material for feedstock, this purportedly brings the production energy down to an equivalent consumption as that of PET or LDPE (40MJ/kg) (Mecking, 2004). Appendix 4 provides further energy equivalents requirements for manufacturing various plastic types. As renewable energy production increases the benefits of biopolymer production may become more favourable from an environmental lifecycle perspective. NatureWorks LLC in the USA announced in October 2005 that their PLA polymer production is now "greenhouse-gas-neutral" through the purchase of renewable energy certificates to cover an amount equal to that of the non-renewable energy used in production which highlights steps being taken in this direction (Omnexus, 2005).

Other degradable plastics are also available, although their status as a BDP is in dispute. Accredited biodegradable plastics undergo hydrolysis making them acceptable in conventional composting plants. Plastic products made from PE can be made to degrade through bio-, UV-, or oxo-degradation by way of addition of special additives into the standard PE resin to promote accelerated degradation at the end of product life. However much debate is taking place as to whether these can be classed as recoverable through composting under the requirements of the EU directive on packaging and packaging waste (IBAW, 2005b; ENDS 2004b).

2.3 Plastics production and consumption in Europe

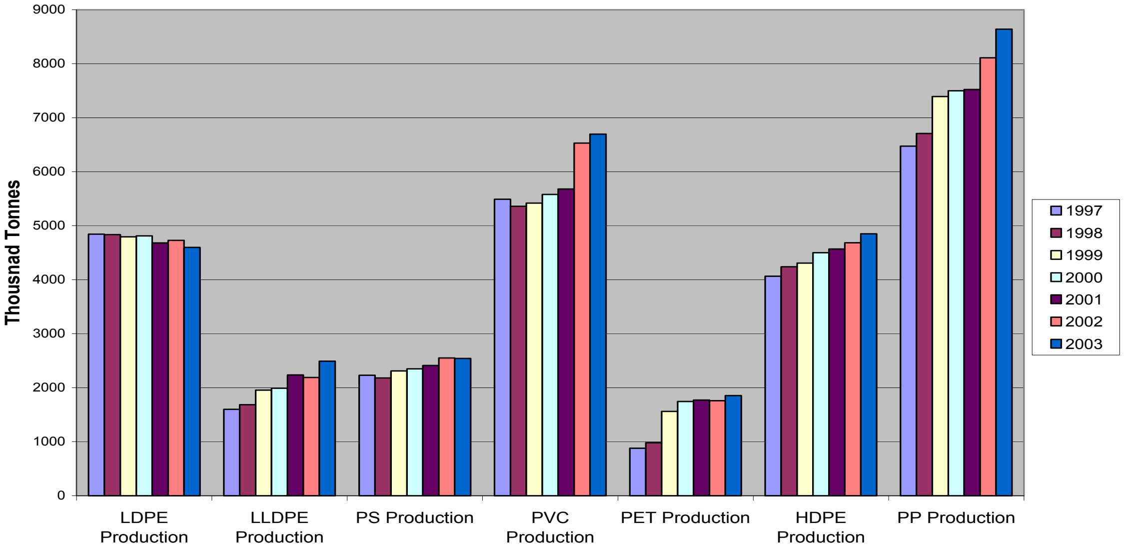

Figure 3: European petrochemical processors production of major thermoplastics, 1997 - 2003 (000 Tonnes) (Source: APPE, 2005 data)

Polymer production, as previously stated, has continued to grow since synthetic polymers first entered the market. Total consumption of plastics in Europe currently stands at approximately 40 million tonnes per year which is estimated to rise to around 55 million tonnes by 2010 (APPE, 2005).

Figure 3 illustrates the Western European petrochemical industries production of some of the major thermoplastics from 1997 until 2003. With the exception of LDPE, which, due to increased development in LLDPE and its associated more competitive price, a general upward trend can be observed for all plastic types presented (APPE, 2005). The general trend for consumption which provides an indication for demand, and subsequently waste arising, is illustrated in figure 3 (tabularised data presented in Appendix 3) depicting total plastics consumption by type in Western Europe.

In terms of quantity of plastic types utilized within Western Europe in 2003, the large-volume thermoplastics families, incorporating polyethylene (PE), polypropylene (PP) polyvinyl chloride (PVC), polystyrene (PS & EPS) and polyethylene terephthalate (PET) accounted for 68 percent of total plastics consumption in typical plastics applications which exclude 'non-plastic'‡ applications. Thermoplastics as a whole accounted for 78 percent of total plastics (thermoset and thermoplastic) consumption in Western Europe in 2003 (Plastics*Europe*, 2004).

During the five year period from 1996 to 2001, PET consumption rose by 124%, representing the largest increase in consumption of all the individual major plastic types utilized for typical plastic applications and continued to be the largest growing plastic type between 2002 and 2003, rising by 8.8% as indicated in figure 4. This has occurred even though PET remains one of the more expensive of the common thermoplastic polymers at 1150 Euros/tonne of virgin batch plastic granules as compared to HDPE for example at 830 Euros/tonne (prices as at 14th August 2005 (PolymerTrack, 2005)).

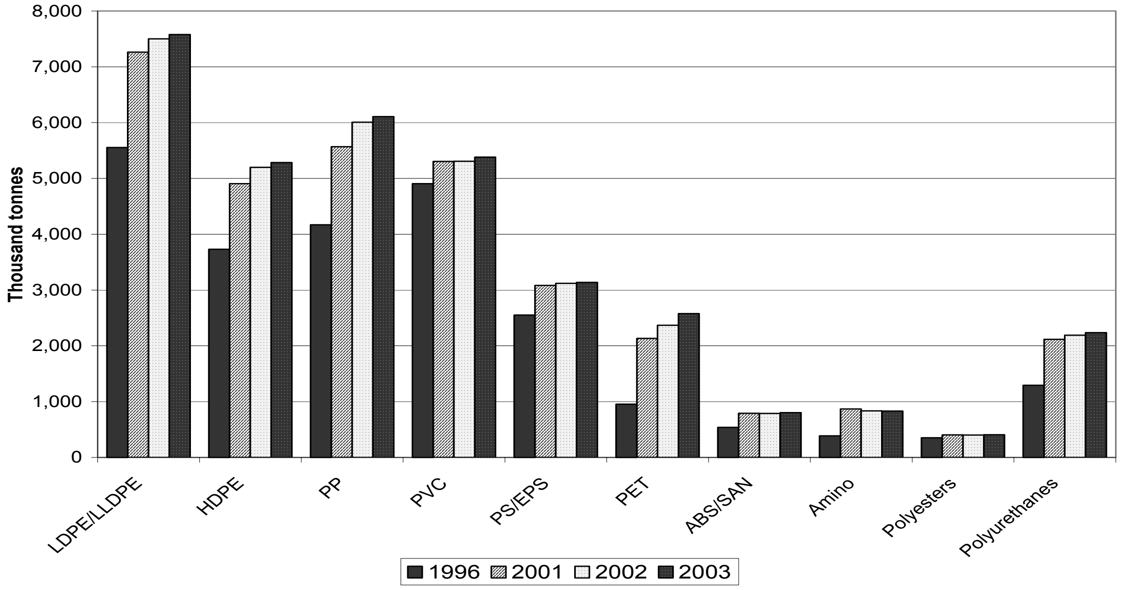

Figure 4: Total plastics consumption by type, Western Europe, 1996, 2001-2003 (000 tonnes) (APME 2004 data).

The strong growth in PET production and consumption can be associated with its primary use as a packaging material. Excluding 'non plastic' applications for PET such as textiles fibres, approximately 90% is utilized for packaging (APME, 2005). Market research has indicated that consumer demand for soft drinks bottles that are re-closable, shatterproof and lightweight, all of which can be met by PET bottles, has dramatically increased in recent years as life styles become faster paced and convenience drinks and foods becoming more common throughout European society (Euromonitor, 2004). Growth in demand and consumption of

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‡ 'non plastic' applications such as textile fibres, elastomers, coatings and adhesives or products that contain only small amounts of plastic material and are therefore not regarded as plastic application. These 'non-plastic' applications contributed to 12.9% of thermoplastics and 39% of thermosets consumption in 2003 (PlasticsEurope, 2004).

non-food and beverage products such as cosmetics and toiletries has also led to high levels of new product development and new found applications for PET bottles along with other packaging materials in recent years.

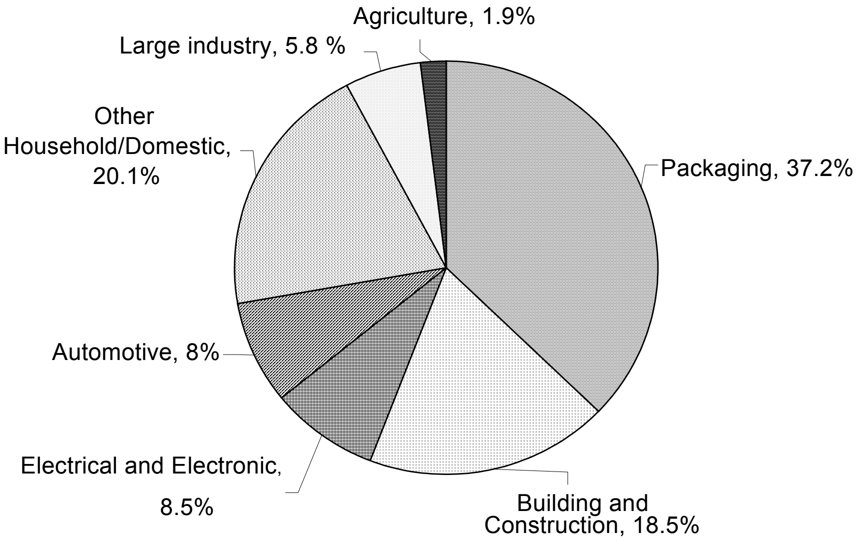

Figure 5: Plastic consumption by sector, percentage of total 39,706 thousand tonnes consumed, Western Europe, 2003(Source: PlasticsEurope, 2004)

With 37% of total plastics consumption being utilized for packaging material within Western Europe in 2003, making packaging the largest sector consumer of plastics (see figure 5), this trend towards increased PET packaging results in a potentially large market for PET products and largely accounts for the increased production and consumption indicated in figures 3 and 4. Blow moulded applications such as PET and HDPE bottles represent around 27% of total plastic packaging consumption (Hannequart, 2004).

Of the near 15 Million tonnes of plastics utilized for packaging purposes within Western Europe in 2003, the largest proportion was in the form of PE and PP films, bags and sacks for domestic and industrial purposes together accounting for 46% of the total, 28% as film applications and 18% for bags and sacks. Approximately 63% of total PE, 31% of EPS and 8% of PVC consumption is utilized for packaging purposes (Plastic*Europe*, 2004). Figure 5 provides and illustrative breakdown of plastics processors' consumption by sector as a percentage of the total (39.7 Million Tonnes) consumed within Western Europe in 2003. These sectors and the polymers/ plastics types utilized within each shall be discussed in section 3 with regard to waste generation.

2.4 Section summary

"Plastics" covers a vast array of materials with an assortment of characteristics and chemical compositions and the total petrochemical derived plastics production world-wide utilizes 8% of the total extracted mineral oils each year contributing to the depletion of non-renewable resources. Although there are many polymer types available, there are only some 20 types that are utilized on a significant scale. The production and consumption of plastics materials continues to grow throughout Western Europe with the large volume thermoplastics families dominating the market and representing 68% of total plastics consumption in 2003. Biodegradable Polymers manufactured from Renewable Raw Materials offer an alternative to petrochemical derived polymers and, although production capacity has increased rapidly within the past decade, they remain a limited niche segment of the plastics industry with 40 **thousand** tonnes produced in Western Europe in 2004 compared to 40 **million** tonnes of petrochemical derived plastics material. Packaging is the main product sector utilising plastics materials (consuming 37% of all plastics processors' consumption in 2003), with 'other' household products including interior and garden furniture, kitchen utensils, etc and building and construction materials consuming a further ~40%.

3. Sources of plastic waste §

With plastics being utilized in so many applications and products throughout Europe today the quantity, type and sources of waste plastics continues to grow. This section aims to identify and illustrate where the major sources of plastics waste arise and the issues which in turn influence the collection and treatment options available.

3.1 General situation overview

Households represent the largest source of post-use plastics waste due to the wide range of products utilized and discarded. The percentage breakdown of the total 21 million tonnes of plastics waste arising within Western Europe in 2002 per sector is illustrated in figure 6. Waste arising is inevitably linked to the plastics production and consumption however certain products remain in use for far longer than other products. Packaging for example generally enters the waste stream within one year of production, where as plastics utilized within the automotive sector tend to remain in use for 10 to 13 years resulting in a time lag between design and discarding. This has important implications for the waste management sector and shall be mentioned in more detail within the subsequent sub-chapters.

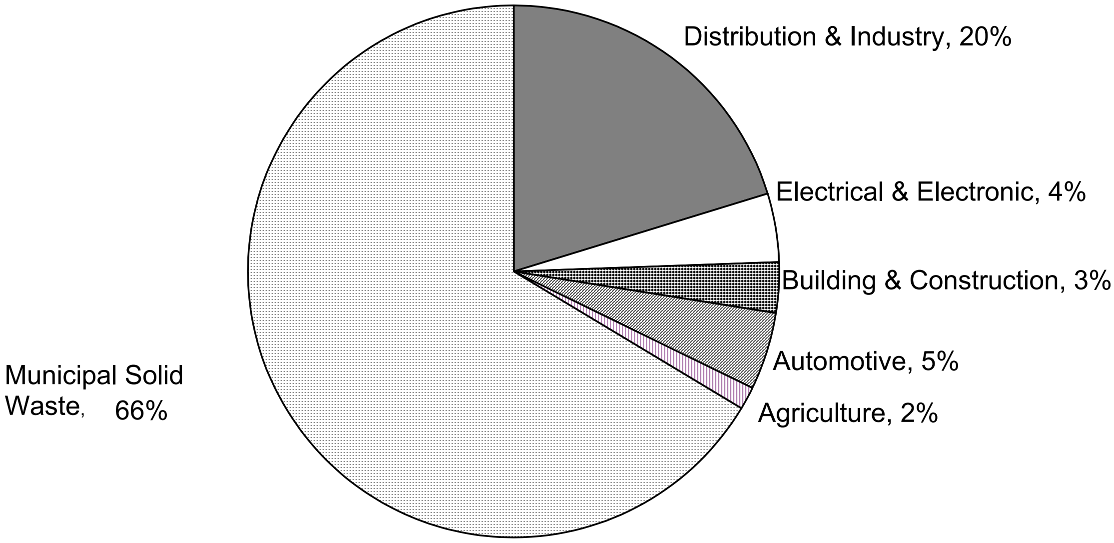

Figure 6: Percentages by weight per sector of total collectable plastics waste arising in 2002 (PlasticsEurope 2004)

Plastic consumption and therefore waste generation also varies substantially between country and indeed specific regions throughout Europe. Within this section a general overview and description of plastics waste generation for Western Europe shall be provided and it should be appreciated that the figures represent the geographical region as a whole and not that of one specific country or region.

[§] Figures provided within this section regarding waste arising refer to "Collectable Plastics Waste". This term is utilized by APME and other organisations due to the fact that not all waste is necessarily collectable due to various reasons. The term therefore refers to the total quantity of end-of-life plastic products, minus the quantity of products not accessible (e.g. pipes that remain in the ground after decommissioning), minus quantity of plastics unavailable for collection due to economic and or technical reasons (e.g. small electronic components with plastics intermingled with numerous other materials) (Hannequart, 2004).

3.2 Municipal Solid Waste

Municipal solid waste (MSW) has various definition differences between individual countries, in the context of this study the term shall refer to households and commercial premises which give rise to waste with similar characteristics to that of households. This waste stream constitutes a significant proportion of the plastics waste arising throughout Western Europe incorporating a range of plastic materials from short lived (approximately 1 year life span) plastic products such as packaging, to longer life (generally up to a 10 year life span) products such as toys, furniture and kitchen utensils. On average plastics represent around 9% by weight and 20% by volume of the total MSW arising, amounting to almost 14 million tonnes of various polymer types in 2002 (PlasticsEurope, 2004; Hannequart, 2004).

Plastic types: The Western European average proportion of different polymers within the entire waste stream has remained relatively constant over time with each fraction growing proportionally. The exception is PET which grew from 8% in 1996 to 12% in 2000 and in doing so has largely replaced PVC in bottle applications which in-turn has seen a decrease from 11% in 1996 to 7% in 2000 (Hannequart, 2004; PlasticsEurope, 2004). A break down of the polymer type content of the 13 Million tonnes of municipal plastic waste (MPW) arising within Western European in 2000 is illustrated in figure 7.

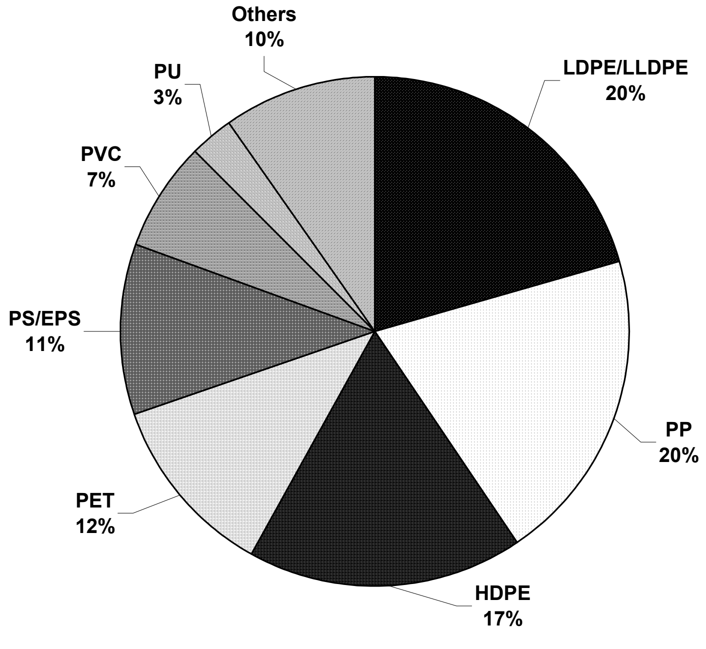

Figure 7: Percentage of polymer types in total MSW stream plastics 2000 (Hannequart, 2004)

As a proportion of the 14 million Tonnes of MPW arising in 2002, packaging represented around 9 Million Tonnes (65%) including food trays, bottles, bags etc. with the remainder consisting of other products including the longer life products previously mentioned (PlasticsEurope, 2004; Eurostat, 2005). Packaging is therefore a substantial proportion of MPW with 70% of all plastics packaging discarded within Western Europe entering the waste system through the MSW stream and 50% (~7 million tonnes in 2002) of all packaging being utilized as food packaging.

Of these various plastic types found in MPW, two distinct groups can be identified, dense (hard) plastics, and soft plastics film on average representing 80% and 20% of the total respectively.

A number of issues surround plastics material arising in the municipal solid waste stream including the fact that household waste arises over a vast geographical area with wide dispersion of households throughout regions, this combined with the variety of different polymer types utilized in different applications represents a challenge for collection companies to retrieve plastics in a homogenous fraction. Contamination from food residues and other contents of the MSW stream also presents a challenge for collection companies and re-processors to obtain a clean fraction in order to recycle. The variety of colours, value added content and complexity of products, and health concerns leading to closed loop recycling of food and beverage packaging being prohibited in certain processes and applications represents further issues to be taken into consideration when planning collection and treatment schemes (Hannequart, 2004; Hulse, 2000).

3.3 Distribution and Industry

Distribution and industry plastics waste consist of relatively short lived products that enter the waste stream within a short time period of being produced, with the exception of reusable pallets, crates and drums which may last 10 years or more. Plastics from this sector can represent a broad range of polymer types due to encompassing all manufacturing facilities. In 2002 this sector produced 3.6 million Tonnes of packaging waste (30% of total packaging waste) which was relatively clean and of homogenous quality consisting mainly of LDPE film. A larger percentage of the packaging utilized within this sector is also reusable when compared to the domestic and municipal packaging products, coming in the form of reusable HDPE and PP crates, pallets and drums. Certain packaging within this sector can however become highly contaminated, especially in the distribution of industrial chemicals.

On a broader perspective, 3.7 million tonnes of production scrap are estimated to be produced each year within Western Europe, of which 1.5 million tonnes is 'in-house' reprocessed and the remaining 2.2 million tonnes gets recycled (with around 10-15% sent to energy recovery or landfill due to contamination levels or other reason inhibiting recycling) by a third party (Johansson, pers comm., 2005).

Pre-use waste, or industrial manufacturing scrap (off cuts from plastics processor production), is often high quality as it has usually not yet come in contact with any contaminants and can be of a single identifiable polymer type. However, there exist issues regarding this from of waste as it can be off poor quality, especially production start-up waste. Off cuts can also become contaminated through mishandling, poor machine maintenance, faulty batch mixing, wrong or new pigments being added. Polymer blends and multi-layer material production can result in unusable scrap within the production facility and been difficult to separate and recycle. It is widely considered that there is little scope for further optimisation of pre-consumer plastics recycling as developments in this field are driven my market forces alone and achieve high levels of recycling (Patel, Thienen, Jochen & Worrell , 2000).

3.4 Automotive waste (End of Life Vehicles)

In 2004, 14.1 million new cars entered into use within Western European bringing the total number of passenger cars in use to approximately 200 million. With the average car expecting to have a road life of around 12 – 13 years, in 2004 approximately 15 million end-of-life vehicles entered the waste stream with the number expected to increase to 17 million by 2015 (Eurostat, 2005).

The amount of plastics utilized in the construction of vehicles is on the rise due to the light weight, low density properties of plastic materials, reducing the over all vehicle weight and thus improving fuel efficiency along with retaining impact strength and aesthetic appearance at an economically favourable rate. In 1989 the average family car contained 70kg of plastics which has increased substantially with the average car produced in 2000 containing approximately 104kg of plastics equating to 9% of the overall car weight (ACORD, 2002) with more recent figures suggesting this proportion has reached around 160kg, equating to 12-15% of the total currently produced average car weight (EMR, 2005). The percentage of plastics utilized in the automotive industry is anticipated to increase substantially in coming years as metal prices increase. Furthermore, fuel prices are also projected to increase causing fuel efficiency to be a more prominent sales feature, these market factors combined with developments in plastics processing will make plastics application in vehicles more attractive to producers (Biron, 2004). Figure 10 illustrates the material composition of an average passenger car constructed in 2000 with a tare weight of 1142kg with plastics being the second largest material fraction by weight.

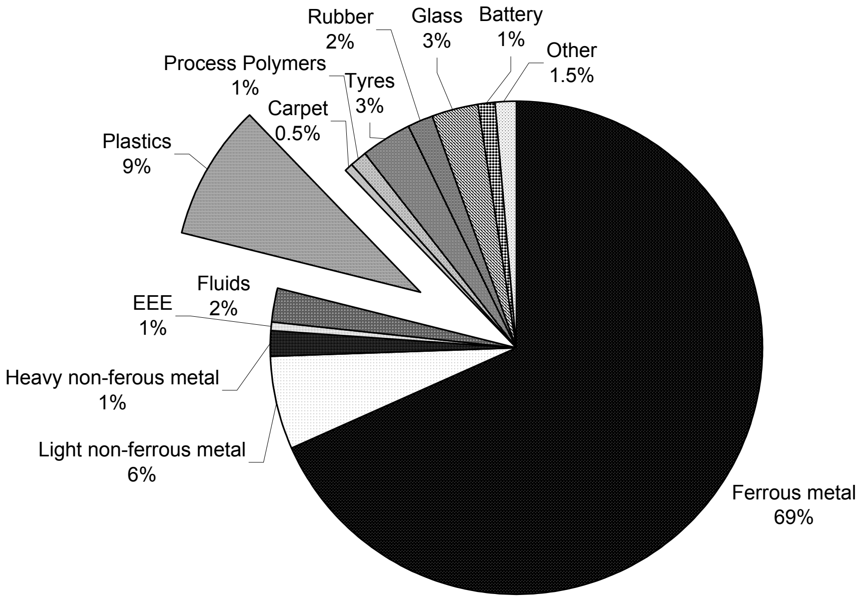

Figure 8: Material breakdown of an average passenger car in 2000 (DTI, 2002b)

Although a typical average vehicle life time is 12-13 years, there are two categories of ELVs one being premature ELVs (those cars that enter the waste stream as a result of an accident), and those which reach the end of life naturally due to failing vehicle road standards as a result of normal wear and tear. The majority of vehicles do however last the intended average 12-13 years. With this in mind, the average plastic waste arising from ELV in 2012 shall be in the region of 104kg per car with around 17 million ELVs resulting in approximately 1.78 million tonnes of plastic waste entering the waste stream from ELVs alone in Western Europe. In 2002 the total amount of potentially collectable plastics available from ELVs in Western Europe amounted to 959 thousand tonnes having risen from 761 thousand tonnes in 2000, and 728 thousand tonnes in 1998 (Plastics*Europe*, 2004; APME, 2002; APME, 2000). This growth is in relation to the substantial increase in plastics utilisation within vehicle manufacturing over the past two decades and also relates to the increasing number of cars in use throughout the European population.

Main plastics utilized: Polypropylene represents the largest plastic fraction (around 40% by weight of total plastics in a typical car produced in 2000) including dashboards, air ducts, wheel arches and bumpers. Other polymer types include Polyethylene in washer tanks, Polyurethane utilized in seating cushion foam, Polycarbonates in headlamp lenses, and glass fibre reinforced Polyamide composites in intake manifolds among others (Jenseit, Stahl, Wollny & Wittlinger, 2003; Waste Watch, 2004). PVC is also utilized within vehicle component parts representing as much as 12% by weight of total plastics fraction in a European car manufactured in the 1990's.

Challenges: Disassembly is labour intensive and time consuming process and therefore only the larger major components such as bumpers, dash boards, washer bottles etc are generally removed. The remaining plastics enter car shredder plants along with the vehicle hulk and after the ferrous and retrievable non-ferrous metals are removed plastics remain as shredder residue which contains a number of polymer types and is heavily contaminated with other particles such as metal shavings and chemicals. As a consequence this fraction has traditionally been unrecoverable for recycling and therefore tends to be disposed off at landfill sites.

3.5 Electrical and Electronic Equipment

Electrical and Electronic Equipment (EEE) is a continuously growing product sector which utilizes a wide array of plastics for several applications and functions. In 2003 some 3.4 million tonnes of plastics in Western Europe was utilized for EEE products equating to 8.5% of total plastics processors' consumption.

Common EEE equipment includes information technology (IT) and telecommunications appliances, medical equipment, cables, and large household appliances such as fridges and washing machines etc. The recent rapid developments in mobile phone technology and home computers have made such products available to the majority of home owners. This has increased demand and supply of E&E equipment (a trend set to continue) resulting in plastics being utilized in larger quantities within these products, especially due to the materials versatility (ICER, 2005). The volumes of plastics entering the waste stream from discarded IT and telecommunications equipment has increased substantially over the past fifteen years with some 145 thousand tonnes of plastic (25% of all EEE waste plastics) being discarded within such equipment in 1995, this increased to 264 thousand tonnes in 2000 and estimates suggest that 475 million tonnes shall be discarded in 2005 equating to around 45% of all EEE plastics waste (APME, 2001).

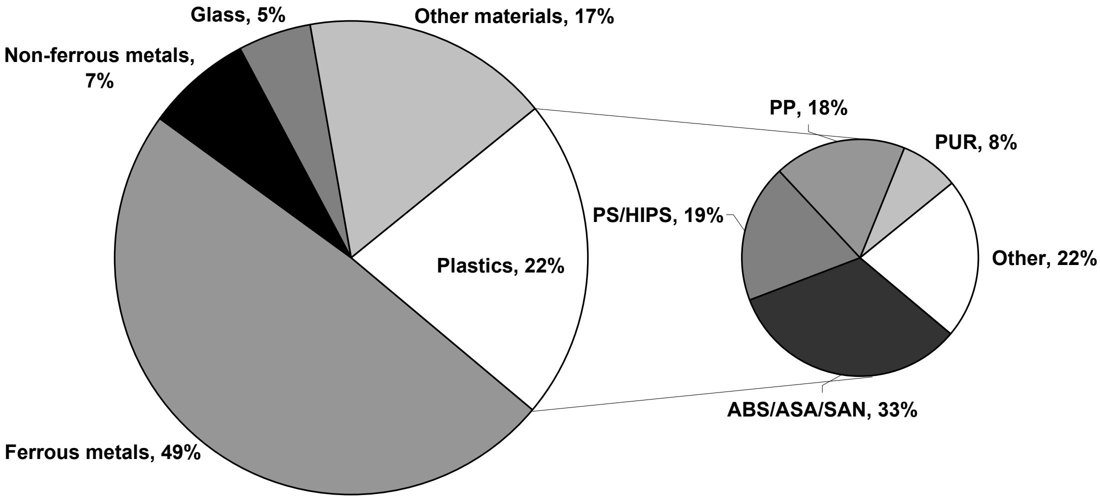

Figure 9: Average EEE breakdown by material (APME, 2001, ICER, 2005)

Main Plastics utilized: Figure 9 provides an illustration of the materials utilized in the EEE sector, as a product group, plastics represent 22% of the weight of average WEEE arising. Of the plastics utilized, the most common types are the engineering plastics styrene copolymers ABS, ASA and SAN which together represented 33%, as well as Polystyrene and

Polypropylene accounting for a further 37% (19% and 18% respectively) of total EEE plastics consumption in 2000 (APME, 2001).

Challenges for end-of-life management: Due to the complexity of parts, variety of polymers utilized in the various applications, and high use of additives such as stabilizers and flame retardants (60% of plastics in a Personal Computer (PC) and 12% of all EEE are commonly treated with flame retardants) within EEE a lot of which is co-mingled with metals and other non-plastic material, the recovery and purity of the plastics entering the waste stream often results in difficulties in separation and recovery of the more complex parts other than the bulky casings. Once collected the processes involved in dismantling and recovering the various waste fractions can be very labour intensive and therefore expensive. This expense can often be recuperated through the separation and recovery of precious metals utilized in EEE allowing the process to be cost efficient. Questions have been raised however as to whether plastics should be recovered at the cost of loss of revenue from more valuable material components (Tanskanen & Takala, 2003; Bohne, Eik, Melum, Michelsen, Storen, Boks, Huisman & Stevels, 2004). The presence of brominated flame retardants (which are commonly used at present) can result in the release of dioxins and furans during the melt process of mechanical recycling and other thermal treatments, these chemicals also affect the melt-flow-index of the plastics making reprocessing into new products and finding market outlets difficult (ICER, 2000). Once large plastic parts have been reclaimed from WEEE the remaining product shell is often shredded in a similar process to ELV shredders. The resultant material is a shredder fluff, often containing various polymer types, although this is dependent on the polymers present, which, as with ELV shredder fluff, can be heavily contaminated with metals and other materials (Simmons, *et al.,* 2003).

The time lag between design, manufacturing and discarding of EEE products is also an issue for all parties involved. With technological innovations and developments rapidly occurring the time between design and end of product life has decreased in some applications, particularly mobile phones and personal computers. This requires waste managers to keep a track of developments in manufacturing in order to effectively and efficiently deal with the complex products entering the waste stream. Other longer life products and products that are stored by consumers prior to disposal also represent a challenge in that older equipment requires to be dealt with at the same time as newer products. Substances found in old equipment which continues to enter the waste stream include cadmium and CFC's found in foams from old fridges which require being removed and treated prior to further treatment or disposal (Simmons, *et al.* 2003).

3.6 Building, Construction and Demolition Waste

The building an construction sector utilized some 7 million tonnes of total Western European plastic processor manufactured plastics for construction purposes (i.e. excluding packaging) in 2003 equating to 18.5% of total plastics processor consumption.

Plastic types: Materials utilized within the building and construction sector throughout Western Europe vary from region to region depending on the climate, building tradition and standards set. Figure 10 illustrates the plastics materials utilized within typical Western European construction applications showing PVC as the most dominant plastic material (Smith, 2002). Plastic applications include PVC window frames and flooring, PVC, PP and HDPE piping, PS and Polyurethane insulation, to PS and PVC insulated electrical wiring. The majority of the plastics utilized within the construction sector are for long-term applications, remaining in place for 40 years or more, until the building is substantially modified or demolished (Simmons *et al.* 2003). However, during the construction process a large amount of plastics are used for packaging and protecting the building materials prior to installation.

PE wrapping, PS filling and PP bags are all utilized to contain, transport and protect building materials (Hannequart, 2004).

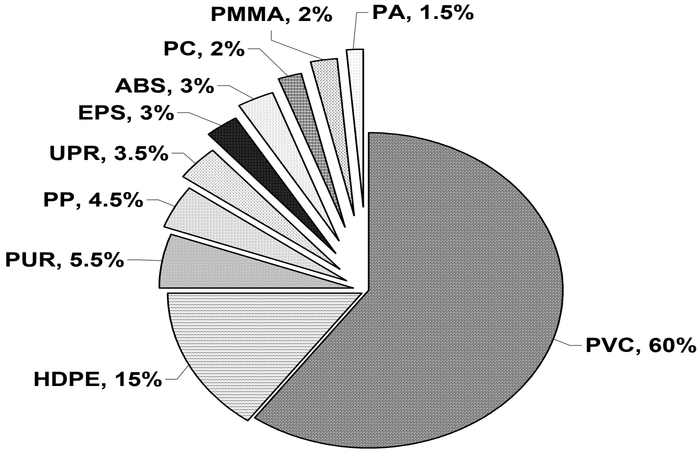

Figure 10: Material breakdown of plastics commonly used in construction sector (Smith, 2002)

Plastics have continually increased in use within the construction industry sine the 1950's and in general the newer the building the higher the percentage of plastics contained within the structure there is. This sector generally retains plastic materials for the longest period of time of all sectors with plastics remaining in their primary role and function for up to 50 years, representing a sector with unique challenges to both designers and waste managers (Bohne *et al.*, 2004).

Data relating to the waste generation from the Building and Construction industry, excluding packaging, indicates that in 2002 around 628 thousand tonnes of collectable plastic waste was generated throughout Western Europe. Packaging, which is included within the distribution and industry sector, if included within the building and construction waste would almost double to around 1.1 million tonnes of available waste not including those not available for collection (i.e. piping remaining in the ground).

3.7 Agricultural waste

In terms of non-packaging plastics consumption (750 thousand tonnes in 2003) and plastics waste generation (311 thousand tonnes in 2003) agriculture is one of the smallest plastics sectors representing approximately 2% of the total collectable plastics waste by weight.

However there are significant issues associated with this plastics waste stream. Agriculture represents a sector where land is available for disposing of waste produced on site either in on-farm dumps or through open burning of wastes arising. This issue has been highlighted recently within the UK where approximately 80% of farmers currently burn at least some of their plastic waste onsite either in the open or within crude steel drum incinerators (ENDS, 2004c). This has been found to results in the release of a significant amount of dioxins and polyaromatic hydrocarbons (PAHs) into the atmosphere each year (ENDS, 2005c). Agricultural waste plastics, if not collected and contained, also cause a serious blight to the landscape, being blown and caught in fencing, trees and bushes, causing aesthetic problems as well as hazards to animals.

Plastics composition: A number of different applications within agriculture utilize plastics ranging from packaging for fertilizers and seeds, piping for field drainage and irrigation, film for field mulching and silage storage, to sheeting films for "polytunnels". The most abundant polymer types within these applications include PE films including HDPE and LDPE and PP bags. These can be relatively short lived applications, often one year, however may be up to 10 years or more especially in drainage piping.

Challenges: Although reasonably large quantities of homogenous polymer types are available for collection from agriculture, there are several key issues that hinder the number of options available for the end-of-life management of these materials. Contamination from pesticides and other chemicals, and degradation from UV light exposure damages the plastics mechanical and chemical properties. This adversely affects their suitability for recycling, as does the possibility of contamination from hazardous chemicals, moisture infiltration, and soil and crop residues which increases cleaning and recycling process costs. Failure to adequately treat the waste product results in contaminants being introduced to the recyclate devaluing their properties and secondary market acceptance (Hannequart, 2004). Due to the fact that most plastics utilized in agriculture are in the form of films, the resulting low density of the collectable waste and wide geographical distribution of agricultural properties in rural areas results in potentially high costs and complicates collection of materials for recycling or other waste management processing.

3.8 Section Summary

Plastics production and consumption is increasing year by year in all of the major societal and industry sectors throughout Western Europe. MSW continues to be the dominating plastics waste producing sector, giving rise to a number of challenges for waste management operations. Primary hindrances to viable collection procedure include; the broad spatial distribution of households, the broad variety of polymer fractions, and the likelihood of contamination from food residues and other MSW fractions. Packaging represents the largest proportion of waste by product type arising mostly (70% of total) within the MSW stream, the remainder (30% of total) coming from retail and industry distribution. Industrial packaging exhibits a higher potential for collection due to more concentrated spatial distribution and cleaner, more homogenous fractions due to a narrower contamination risk.

WEEE and ELV plastics represent substantial challenges for the collection and separation of polymer fractions due to their complexity. Contamination from other waste materials and the time lag between design and end of life also increase recycling complexity. This factor is even more prevalent in the building and construction sector where time lag can be up to 50 years representing significant challenges for designers and waste mangers a like. For designers a prediction of the waste treatment options available and demands from legislators in the future (i.e. 50 years from the design stage) need to be taken into consideration. Waste managers must also have the capabilities to manage products which where manufactured 50 years in the past. The agriculture sector, although representing the smallest quantity of plastic waste production has unique considerations due to the possible occurrence of on-farm disposal by dumping or burning which can lead to significant amounts of air pollution. This coupled with the wide geographical dispersion of waste producing sites and the low weight to volume ratio of the plastics material impacts the waste management planning process by reducing the number of end of life treatment options available.

4. Issues in plastic waste disposal and treatment options

Having introduced production and consumption of the major different plastic polymer types, how they differ in properties, their applications and sources of waste arising, this section aims to introduce the reasons why, when these materials become waste, they can not all be managed in the same way. Depending on whether the polymer is thermoset or thermoplastic; degradable or biodegradable; the additives present or required in different applications; whether it is a polymer blend or the product is constructed from composite material or laminates; and the quantity and purity of the plastic utilized in products and applications, all have direct implications on the end-of-life management option whether that be mechanical recycling or feedstock recycling, incineration or landfill. The reasons why landfilling is seen as the least desirable waste management route and a general introduction to the various alternatives available depending on the properties of the plastic type shall be presented within this section.

A number of Life-cycle-assessments (LCAs) have been conducted on various plastic waste management treatment options throughout Europe. The findings of these studies are presented within the subchapters below, however, in general the findings support the waste hierarchy. Regarding the group of options presented within figure 11 there is evidence to support a claim that from an environmental impact perspective mechanical recycling of the major thermoplastics is the most preferred option. This is outlined by the flow of the chart when moving across the diagram from right to left, i.e direct disposal in landfill generally has a greater impact and therefore the least preferred option. However exceptions do exist (which shall be expanded upon) and studies have shown (Wollny *et al.,* 2002) that there is no single optimal solution, as performances vary from region to region and between treatment facilities, therefore an integration of several treatment methods is often justifiable.

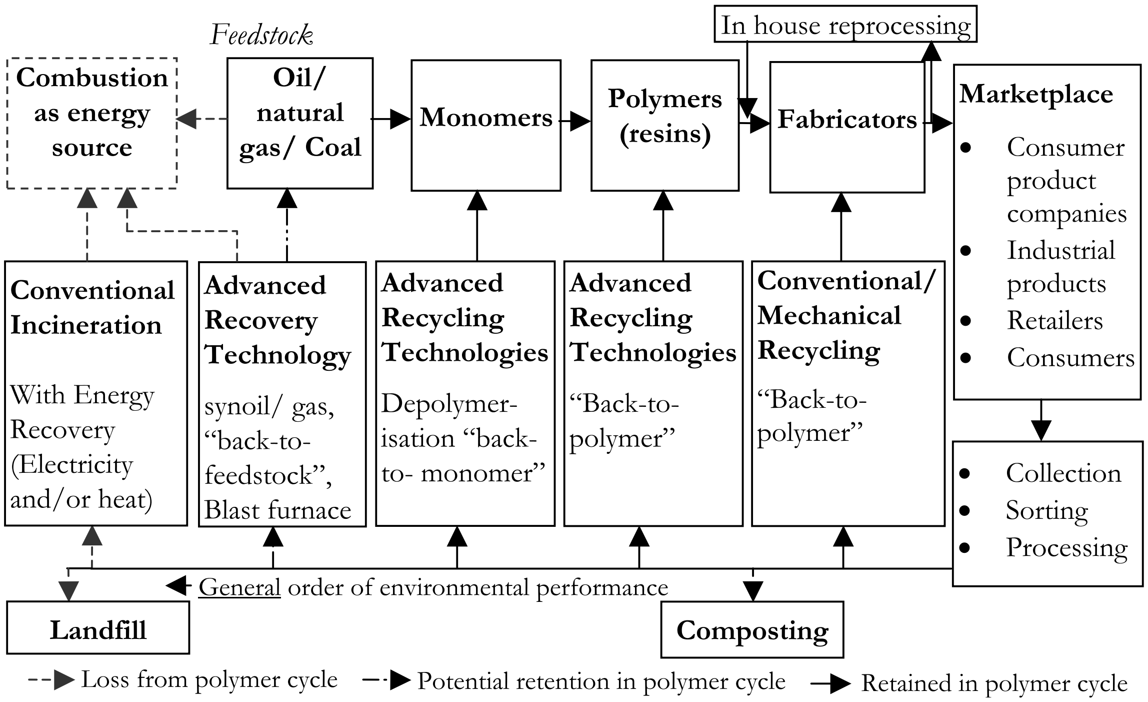

Figure 11: Simplified overview of Plastics waste management options

In order to achieve the optimal environmental solution by market forces alone, recycling has to be economically profitable to companies. The economic profitability of recycling materials is reached when the net recycling costs (i.e. the overall costs for collection, separation and processing minus the revenues from sale of the recyclates) are lower than the prices for alternative waste management routes such as landfill and incineration (COM, 2000). If economic profitability cannot be reached, waste recycling will not take place under free market conditions which has been the case in the past and the reasons for this shall be expanded upon forthwith.

4.1 Landfill

Landfilling has traditionally been seen as an easy and cheap method for disposing off all waste materials generated by society and therefore has been and remains the dominant waste disposal option. Relatively high abundance of void space in many countries due to past and present excavation activities such as mining and quarrying (i.e. mineral and aggregate extraction) gave rise to void space ideal for waste disposal at low cost. However, as these excavation activities have decreased in recent years while waste production has increased throughout Europe, void space has become increasingly scarce. This has subsequently led to the realisation that the environmental impact potential of landfill must be considered (Williams, 2005). Increasing value of land particularly around major urban populations and growing public opposition such as the NIMBY (Not In My Back Yard) objection to landfill development activities close to population centres has also led to reduced the rate of landfill site construction. For these reasons the number of operating landfill sites is decreasing across Europe and landfill costs are anticipated to rise as less void space is available and more stringent construction requirements and operating practices are imposed making the landfilling of waste less attractive to waste handlers on economic grounds.

Materials degrade within landfill, especially biodegradable waste materials which undergo anaerobic digestion to release gas and in particular methane (which amounts to approximately 64% of the composition of typical landfill gas (Williams, 2005)) which is a potent Green House Gas (GHG) and contributes to atmospheric pollution. Equally polluting are the leachate liquids which may carry heavy metals and harmful substances into the groundwater. This is of particular pertinence to biodegradable polymers which enter landfill sites, as these may anaerobically degrade within the conditions present in landfills and contribute to both gas and leachate production[**]. Although methane emanating from landfill sites can be captured and combusted for energy production, this is not, as yet, practiced in every landfill throughout Europe, and where it is practiced it is inherently difficult to capture all gas arising and ensure it is treated or utilized in the optimal way. The negative externalities (i.e. the impacts which are not, if left to market forces alone, reflected in the financial price paid for landfilling waste) are therefore high and consist of not only resource loss and environmental harm from gas and leachate emissions on human health and the biosphere, but also noise, increased traffic, dust, odour, vermin etc. which can all be attributed to landfill operations.

Although synthetic petrochemical derived plastics (as apposed to RRM based biopolymers) are regarded as a minor contributor to gas emissions from landfill[††] due to their relative stability and resistance to degradation from microbial breakdown (mainly as a result of their chemical composition, stabilising, antimicrobial and other additives utilized) plastics do contribute substantially to void space utilisation due to their high volume. It has been estimated that around 25% of the void space already utilized within currently operating landfills is taken up by plastics waste (Hulse, 2000). One associated problem with regards to this high volume of plastic (especially packaging) is that landfill gas can become trapped within the pockets created

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[**] Uncertainties exist regarding the extent to which biopolymers degrade in landfill and the volumes of methane produced, it is however regarded that CO^2 production is sequestered in growing new bio-polymer feedstocks (Bohlmann, 2005).

[††] The full implications of plastics in landfill sites is not, as yet, fully known as plastics have not been in landfills for long enough to determine how long they take to degrade and what effect this has on the environment and landfill site.

making extraction and controlled capturing of gases for energy recovery purposes problematic. High volume plastics waste may also lead to landfill instability and settlement problems (Williams, 2005). The conditions within the landfill site also result in the release of additives utilized in the manufacturing of the plastic products. A study commissioned by the European Commission in 2000 into the behaviour of PVC in Landfills concluded that the conditions during the acetogenesis phase of a landfill (where pH drops to around 4 due to the creation of acetic acid) can cause the release of heavy metals such as lead (lead in PVC stabilizer additives is estimated to contribute to 28% of the total lead introduced to landfill) and the aerobic conditions at the beginning of a landfill life can cause up to 40% of phthalates contained within soft PVC to be released into landfill gas and leachate (ARGUS, 2000). The release of hazardous substances within plastics disposed off in landfill is not restricted to PVC however, and a number of plastics which use heavy metal additives or other potentially hazardous substances in their manufacture have been found to give rise to undesirable substances in landfill emissions (Williams, 2005). Items of electrical and electronic equipment which are often encased in plastics also contribute to heavy metals found in leachate and gas emissions.

4.2 Incineration

Incineration, which, after landfilling has become the second most dominant plastics waste treatment option, involves the full oxidative combustion of waste material within controlled conditions. A benefit of incineration over landfill is that it can accept co-mingled waste without the requirement for extensive separation and reduces the waste volume and the fact that the process can be carried out close to where the waste is being generated due to their relatively compact nature. However, landfills are generally required close by incineration facilities in order to accept bottom ash and fly ash (which is of a hazardous nature). Incineration does not produce the potent green house gas, methane (although it does produce CO_2 along with other environmentally detrimental gases) (Williams, 2005). The incineration of waste without energy recovery was previously widely practised as a means to merely dispose of waste however this has now largely diminished throughout Western Europe, although is still in use in some regions. This type of disposal can be seen as more detrimental than landfilling plastics waste as it makes no use of the material resources whilst contributing to atmospheric pollution to a larger extent than landfilling (Sander *et al.*, 2004).

Plastics offer a valuable and one of the most significant forms of high calorific material for incineration plants which recover the energy from the waste. The average calorific value of polymers commonly found in MSW is in the region[⌗] of 40MJ/kg which compares well to that of coal being approximately 31MJ/kg although the calorific value of mixed waste is lower due to the high moisture content and presence of low calorific waste, resulting in mixed MSW having a calorific value of 7 – 15 MJ/kg (European Commission, 2005). However as plastics consume up to 90MJ/kg of energy to produce a virgin raw polymer material, the energy recovered is comparatively low (Biffa, 2005; Bourstead, 1996).

The thermal efficiency of MSW incineration plants varies between individual facilities, thermal recovery as electricity, steam or heat is reportedly as high as 80% in certain plants although this is the exception and not the norm (EIPPCB, 2005b). Within Germany the total energy recovery ratio of all 57 MSW incinerators in operation in 2000 was found to be approximately 39%, with 8% arising from electricity production, 15% from district heating, and 16% from process steam generation. The recovery ratio variances between plants ranged from 11% to

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[⌗] MSW plastics typically comprises of approximately 60–65% polyolefins (i.e. polyethylene and polypropylene) with a calorific value of 42 MJ/kg, 15–20% polystyrene - 40 MJ/kg, 10–15% PVC - 18 MJ/kg, and 8% composites - 20 MJ/kg (Biffa, 2005)

73% (Wollney *et al.*, 2002). The revenues obtained through the sale of the electricity and hot water generated can contribute to the overall economic viability of the plant, however revenue obtained from the sale of electricity or heat, regardless of efficiency, does not cover incineration plant capital investment and operating costs and are reliant upon gate fees to cover financial costs. Gate fees charged to achieve high thermal efficiency are higher than that of landfills operating without intervention to increase their costs. Plastics are of high calorific value and therefore a preferred waste stream for incineration, they are however low weight and as gate charges are applied on a per weight basis they do not create significant revenue. It is the heavier fractions of waste e.g. biological waste such as food residues which are heavy due to their moisture content which enable incinerators to operate on a cost efficient basis (Wollney *et al.*, 2002).

Although plastics waste are beneficial in terms of increasing the overall calorific value of waste and in turn aiding the generation of electricity and district heating waters, they do also pose a number of challenges. High volumes of plastics (≥70% of waste feed) entering a mass burn incinerator at any one time can cause some problems within the combustion furnace. These include issues with controlling the burn rate and in turn the furnace temperature which should be fairly constant relative to the boiler optimum functional temperature, and the fact that if volumes of plastic are too high, they may melt and flow down the grate (utilized in certain plants) affecting the residence time combustion efficiency (Williams, 2005; Hogland, Nyström, Schelin & Tamaddon, 1991). PVC in the MSW stream is reported to contribute to 38 to 66% of the total chloride content of the waste and 10% of the Cadmium content (Jacquinot, Hjelmar & Vehlow, 2000). Through combustion the organic component of PVC is destroyed leaving the chlorine to react with hydrogen to form hydrogen chloride and hydrochloric acid in solution which may damage equipment, can enter the flue gas and potentially be released into the atmosphere or can react further with inorganic compounds in the waste such as mercury and create metal chlorides (POST, 2000). Although these pollutants can be removed from the incineration emissions through the use of scrubbers and flue gas treatment, it has been determined that where PVC is present in the waste, the residues from these treatment processes have elevated levels of leachable pollutants which are required to be disposed off at hazardous waste landfill sites (Jacquinot *et al.*, 2000).

Other main pollution concerns associated with incineration of plastics waste include the production of dioxins, acidic and other gases (including hydrogen fluoride, sulphur dioxide, nitrogen oxides, carbon monoxide and carbon dioxide), heavy metals and particulate matter (POST, 2000; Williams, 2005). These are present in the bottom ash, fly ash, combustion gases and liquid effluent from gas cleaning technologies.

On comparison with other available treatment alternatives for plastics, waste incineration with energy recovery from an environmental impact perspective has been determined to be more advantages than landfill. Where high energy recovery ratios from waste calorific value to energy recovered is above 50% (including electricity production and heat utilisation in district heating or other system) incineration can be seen to be on par or even advantages to advanced (feedstock) recovery at lower financial cost (Heyde & Kremer, 1998 & 1999). However, the source of energy which waste incineration is substituting or displacing must also be taken into consideration whether this be coal, natural gas, biomass or other renewables (as for advanced recovery) as this has direct impact in the environmental benefit of energy from waste environmental performance (Wollney *et al.*, 2002).

4.3 Mechanical recycling

Mechanical recycling (also referred to as conventional or melt recycling) in simplistic terms is a process whereby thermoplastics are reclaimed from the waste stream, washed and contaminants removed, flaked or granulated into small pieces (regrind) which can then be reprocessed directly as polymer feed or repelletized for sale to plastic product manufacturers. This is regarded as the most environmentally preferable plastics waste treatment option though there exist a number of technical, financial and logistical complications making it a complex treatment option compared to landfill and incineration (an overview of technical limitations is provided in appendices 5 and 6). In a closed loop system (the process of utilising recycled material for the production of new products on the same quality level as the original material was utilized e.g. plastic bottle into a new plastic bottle) mechanical recycling is applicable only to thermoplastics (as thermosets and biopolymers can not be remelted whereas thermoplastics can).

There are several environmental and economic benefits from mechanically recycling certain petrochemical based polymers. The preservation and reduction of finite virgin raw material use and extraction impacts have benefits in the long term (Pickering, 2005). Energy savings are also a significant incentive for the recycling of many forms of plastic provided that collection costs and impacts there from, plus the impacts from recycling are less than that of producing virgin materials. For example in the case of PET which as previously mentions requires in the region of 80MJ/kg energy equivalents for production, Matthews (1998) concludes that the production energy (from post consumer collection to production of regranulate which substitutes virgin polymer) ranges from 8 – 30MJ/kg.

From LCA research conducted in this field, mechanical recycling of homogenous thermoplastic waste streams, when recycled in a closed loop system or substituting virgin plastics in alternative products and applications (open loop system), outperforms feedstock recycling, energy recovery (mixed waste incineration and mono-incineration) and landfill in terms of ecological benefit especially in terms of greenhouse gas emissions and primary energy consumption (Wollny & Schmied, 2000; Wollny, Dehoust, Fritsche & Weinem, 2002; Pergugini, Mastellone & Arena, 2005). This benefit is inclusive of any external environmental burden arising from collection and transportation, although does rely on homogenous polymer materials being reclaimed or separated with relatively little contamination. Contamination from non-plastic-polymeric materials i.e. food residues, metals, labels, glues, moisture and certain additives (i.e. lead and brominated flame retardants which disperse through recyclate) present an additional problem for mechanical recycling as these contaminants often require substantial amounts of pre-treatment in order to remove them and obtain a high quality regranulate. This contributes to the higher financial cost associated with this treatment option and therefore is not usually preformed on open market conditions without some form of incentive or intervention. Given the number of polymer types and waste streams in which they arise, the separate collection and separation of plastics from other materials arising in the waste substantially influence the ability and financial viability of mechanical recycling.

As previously discussed there are a large number of polymer and resin types within the thermoplastic family. These different polymers tend to repel each other if reprocessed together due to their different chemical compositions and the amplified effect of intermolecular forces on the solubility of the polymer types (see appendix 5). Therefore, in order to create a good quality, valuable recycled plastic material which offers the benefits mentioned it is important to have a homogenous resin stream in order to retain the properties associated with the different thermoplastic types (EIPPCB, 2005; Goodship, 2001; Athalye, 1995).

Mixed polymers can however be processed together in blended material through the use of compatibilizers which aid the bonding and enable two or more polymer fractions to bond, although this may affect the heat induced degradation of the polymer chains by requiring the polymer specific melt flow index to be exceeded (see appendix 5). Mixed polymer recyclate which does not meet quality requirements that allow it to substitute virgin plastics can also be utilized in alternative applications substituting other materials such as wood, concrete and steel. However the environmental benefits from this 'down-cycling' activity have been found in some studies to be far smaller than those associated with higher quality homogenous polymer recycling and may even have negative environmental impacts depending on the material and application they substitute (Wollny & Schmied, 2000). However, it has been noted by other authors that there has been little detailed investigation of these practices incorporating the whole life cycle perspective including the benefits from weight reduction, less chemical use in preservatives commonly required for wood applications, the potential for extended product life compared to wood, and reduced maintenance costs (Simmons, Dandy, Smith, Kuss-Tenzer & Crofts, 2003).

In terms of promoting further establishment of mechanical recycling a report produced in 2003 by 'Waste Watch' and 'Recoup' in the UK entitled "*Plastics in the UK economy*" states that the development of markets for recycled plastics is "*one of the most important drivers for increased plastics recycling*" and that "*demand for recycled plastics will increase when there is a reliable supply of appropriate quality recyclates*".

The main identified factors to take into consideration with mechanical recycling of post consumer waste therefore include:

- The requirement for a relatively clean source of post consumer or scrap plastics free from contaminants, or the means to effectively and efficiently clean the materials;
- A need for efficient and effective separation techniques and or technologies in order to obtain a homogenous polymer fraction of thermoplastic resins whether through investment in automated separation or manual separation processes;
- Establishing and developing end-use markets for materials.
- Cost competitiveness with virgin plastics material (including the costs of collection, separation, reprocessing and delivery).

4.3.1 Advanced Recovery Technologies

As mentioned, thermosets can not be mechanically recycled in the same way as thermoplastics, and thermoplastics undergo degradation along with other identified limitations such as requiring a relatively clean and preferably homogenous material for reprocessing. Therefore alternative methods are available in order to recycle and recover both these materials from the waste stream.

4.3.1.1 Chemical Recycling

Chemical recycling covers a range of techniques which depolymerise polymers by reversing the polymerization process to result in the basic chemical fractions originally utilized (back to polymer or back to monomer) which can be re-polymerised once again into new plastic materials. This, again, generally requires separating the plastics into homogenous resin types (although contaminants such as non-polymeric materials e.g. food residues, glues, and additives may be removed in certain processes) and then depolymerising them back to their basic monomer units. Condensation polymers (monomers that bond through their reactive end groups joining and expelling water or other small molecule to form a polymer chain, examples include certain polyamides, PMMA, PET, PC and polyurethanes) can be depolymerised through various solvolysis processes including glysolysis, methanolysis and hydrolysis among others which break long polymer chains into short-chain oligomers that are repolymerized into virgin polymer (Ashraf, 2004; Pergugini *et al.*, 2005).

Alternatively, in certain conditions and where addition polymers (polymers that are formed from the breaking of unsaturated monomer double bonds re-bonding with each other to form polymers such as PE, PP and PS) are the material feed, the original pure monomer units can be reclaimed through thermal treatment if the material is homogenous and the thermal processes are optimised through use of a catalyst to enable the depolymerization reaction (Goodship, 2001).

Chemical recycling, due to the more technical nature, can have associated higher investment, maintenance and operating costs than mechanical recycling. Therefore without incentives to utilize these treatment options, market forces alone have not encouraged industry to invest and utilize this option as the environmental gains are not reflected in the market price. Studies on operational processes also suggest that these processes also have a slightly higher environmental burden than mechanical recycling however these are reportedly less than for alternative treatment methods such as feedstock recycling, incineration and landfill, particularly where the end product is of a high standard suitable for substituting virgin polymers on a one to one basis (Wollny & Schmied, 2000).

4.3.1.2 Feedstock Recycling

Feedstock recycling refers to a group of technologies that thermally breakdown (depolymerise) the large polymer molecule chains within plastic resins into smaller hydrocarbon chemical intermediates in the form of synthetic oil, gas (usually in combination) and or wax reflecting the hydrocarbon properties of the original feedstock resource utilized in the material production (i.e. petroleum) (Perugini, Mastellone & Arena, 2005). This is of particular use for mixed plastic waste as thermal treatment of this kind is less constrained by the presence of contaminants and mixtures of polymers and more versatile than mechanical (and chemical) recycling. These processes are required to take place in the absence of oxygen (i.e. anaerobic condition systems such as pyrolysis or hydrogenation) or in the near absence of oxygen (i.e. in the controlled oxygen environment of gasification) so as not to result in combustion and instead enable the release of chemical feedstock products (Mayne, 2002). The resultant hydrocarbon feedstock can either be further processed (e.g. by naphtha steam, or catalytic, cracker) into monomer or alternative petrochemical derived products, or can be utilized as a fuel product (i.e. synthetic oil or gas as a conventional petrochemical fuel substitute or directly in a turbine for electricity generation). In processes that produce a synthetic oil or gas, which can be stored and transported, the main benefit is that recovery is spatially and temporally separated from the production process. The product can therefore be utilized for a greater variety of applications from small to large scale electricity production to vehicle fuel utilisation (Sander, Jepsen, Schiling and Terbert, 2004).

The capital investment and running costs associated with feedstock recycling have traditionally been relatively high compared to landfill and incineration. This is due to the technological developments in these systems having only been researched and developed recently; they are therefore at an immature stage. The environmental benefit of feedstock recycling is dependent upon the efficiency of the process, the end product use and products these substitute, and the efficiency of alternatives available in the area (i.e. energy recovery efficiency of incineration plant). Research suggests that compared to the majority of current energy from waste incineration plants, feedstock recycling does offer environmental benefit, however exceptions do exist where high energy recovery efficient plants are in operation (requires both electricity production and district heating/ steam heat utilisation with high recovery ratios >50%) (Radaal, Krough, Nyland, Hanssen, 2001; Wollney *et al.*, 2002; Pergugini *et al.*, 2005). It is apparent that there exist associated benefits from plastics feedstock (as well as mechanical and chemical) recycling as apposed to mixed waste incineration and landfill. It has been suggested that inclusion of plastics in a source separated and centralized separation system increases participation and sorting of other recoverable materials including paper board, glass and metals (Wollney *et al.*, 2002, Simmons, *et al.*, 2003)

4.3.2 Treatment of Biological waste

Biological treatment is well grounded as a waste treatment option for biologically degradable waste fractions. Biological treatment (or 'organic recycling') of biodegradable plastics can either occur aerobically (composting) or through in-vessel anaerobic digestion (biomethanization). Each process produces much the same final humus material however the bi-products of the treatment process differ. Aerobic composting (re)releases carbon dioxide and water vapour into the atmosphere where as anaerobic digestion shall release methane and water vapour (which, if carried out in purpose built facilities, can be captured and utilized in energy production). The materials obtained have the possibility of being returned to the land and returning valuable nutrients to aid the growth of new plant materials for biopolymer production, or utilising the microbes that break down the biopolymers during the composting digestion stage as a feedstock for the production of new PHA polymers. Combustion with energy recovery of RRM based bio-polymers can also provide a renewable energy source although the calorific value of these materials has not been determined.

However, as with mechanical recycling of petrochemical based polymer, bio-polymer materials require separation from other wastes in order to obtain high quality compost. The infrastructure costs associated with collection and biological treatment facilities is also relatively high and revenues obtained from the sale of resultant product do not generally cover these costs, therefore landfill, where no incentive for separation is required, would be the preferred option based on a market approach.

4.4 Integrated Waste management

In dealing with the end-of-life management of plastics (or any material) integrated waste/resource management has gained increasingly broad acceptance among policy makers and industry leaders in recent years (Ashraf, 2004). This is in light of that fact that different waste streams contain similar wastes that can be integrated for treatment together. Such a realisation has led to an understanding that in order to achieve optimal environmental benefit when dealing with waste currently arising, an integration of various treatment techniques and approaches is most desirable. This has been compounded by public opinion and geographical variances which have a strong influence on what management options are available, acceptable and implemented.

Integrated waste management, as defined by Williams (2005) is "*the integration of waste streams, collection and treatment methods, environmental benefit, economic optimisation and societal acceptability into a practical system for any region*" thereby providing a range of waste processing and handling facilities optimising cost efficiency with environmental protection standards. Figure 12 provides an illustration of the integrated waste management concept and aspects that require to be optimised to achieve an optimal management system (IWM and LCA, 2004).

The concept of integrated waste (or resource) management is of particular relevance in dealing with post consumer plastics material, as a variety of different treatment and end-of-life management techniques and technologies exist and are required - as previously outlined. With the growing development of both biopolymers and petrochemical based polymers, along with the various limitations and aspects concerning various available treatment options, there is a need to utilize each of these to achieve the optimal management system.

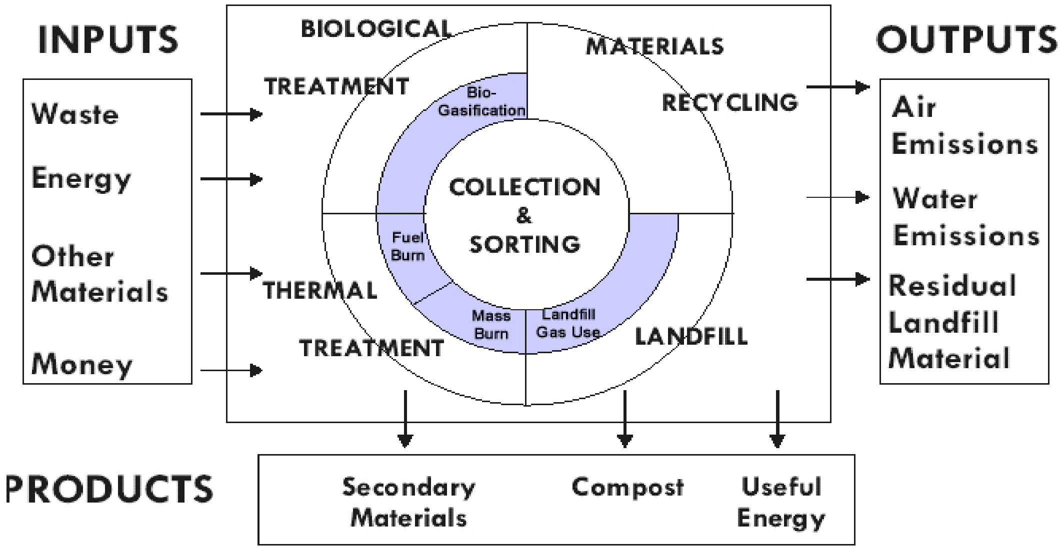

Figure 12: Integrated waste management system diagram (IWM and LCA, 2004)

The three main issues that are required to be taken into consideration within an integrated management system are therefore identified:

- **Economic optimisation** costs associated with waste management systems should be acceptable to all societal sectors and stakeholders including: householders; commerce; industry; institutions; and government and the management options should be the most cost efficient.
- **Social acceptability** requires that the waste management system meets the needs of the local community, and reflects the values and priorities of that society.
- **Environmental effectiveness** requires that the overall environmental burdens of managing waste are reduced, both in terms of consumption of resources (including energy) and the production of emissions to air, water and land (IWM and LCA, 2004).

It is apparent from research literature that a combination of treatment options complementing one another and reviewed on a regional/local level is required to achieve the most environmental, social and economic benefit. Mechanical recycling of clean homogenous polymers with the resultant recyclate replacing virgin polymers on a one to one basis is preferable where applicable and if collection is achievable at minimal environmental cost. Chemical recycling of waste polymers unsuitable for closed loop mechanical recycling, composting of biopolymers, and feedstock recycling are also deemed to be environmentally and socially preferable over incineration and landfill, and for some polymers that can not be mechanically recycled, are the best available option. Energy from waste incineration is also seen to be a viable route where the thermal recovery ratio is high. However, although each of these processes, individually or collectively, can offer clear environmental benefit, market forces alone generally do not allow the establishment and use of these options.

The financial cost of waste treatment, which does not include the environmental externalities or reflect the full economic gain of achieving the most environmentally sound system, often results in the financially cheapest option being utilized. In many cases this is the direct disposal of waste in landfill, or incineration. Therefore intervention is often required to promote environment friendly and socially acceptable waste treatment.

5. European Union Policy Intervention

This section aims to identify the European Union's stance on how plastic materials which enter the waste stream are managed and the desired treatment options highlighted and defined within the EU's overall waste strategy, vision and goal. The policies stemming from the EU in order to promote the identified most desired options for dealing with the waste arising and the related targets and goals shall be provided in order to determine what shape the plastics waste management sector should be as proposed by the European Union's intentions.[§§]

5.1 Background to EU position on waste management

Since the early 1970s the European Union has had a focus on environmental protection and management. In recent years this attention has increased with the introduction of a variety of initiatives, programmes, regulations, and directives relating to environmental activities. In 1972 the first European Environmental Action Programme (EAP) was drawn up largely as a result of the recognition that if the evolving goals of the EU in relation to encouraging economic expansion and improving quality of life were to be achieved, then attention to environmental protection was a requirement. To date the EU has produced six EAPs covering a broad range of environmental issues resulting in the introduction of increasingly progressive policies regarding waste management practices which have evolved from the concept of pollution control, through pollution prevention, to today's sustainable development approach (Williams, 2005). During the fourth EAP (1987-92) a European Community strategy for waste management was introduced and established the waste management hierarchy (figure 13) as a long term goal for the EU to strive towards indicating options in order of preference with relation to environmental performance and desirability. The hierarchy is largely founded on five principles of waste management stemming from the EAPs which have established a focus on: waste prevention; recycling and re-use; promotion of recovery (inc. energy recovery); minimising and improving final disposal and monitoring; and regulation of waste transportation and remedial action (Europa, 2004).

The Sixth EAP which covers the period from 2001-2010 stipulates the specific aim of establishing "*better resource efficiency and resource and waste management to bring about more sustainable production and consumption patterns, thereby decoupling the use of resources and the generation of waste from the rate of economic growth and aiming to ensure that the consumption of renewable and non-renewable resources does not exceed the carrying capacity of the environment*" (OJ L242, 2002). The programme therefore reiterates the view that total waste generation should be reduced. For waste that is still generated the 6th EAP states as an objective that this should be "*either reintroduced into the economic cycle, especially by recycling, or are returned to the environment in a useful (e.g. composting) or harmless form*" and that residual waste requiring to go to final disposal are kept to an absolute minimum being safely destroyed or disposed of with no impact on environment or health. This is emphasised by establishing targets to reduce the quantity of waste going to final disposal by around 20% by 2010, and in the order of 50% by 2050 with 2000 as the base line standard year (COM, 2001a). A further stated objective is that waste is disposed of as closely as possible to where it is generated incorporating the 'self-sufficiency' and 'proximity' principles of the waste framework directive (see section 5.2.1).

[§§] Although it is appreciated that prevention is better than cure and that the EU's overriding philosophy and aim is to promote the avoidance, prevention, minimisation and reuse of materials common within our society as highlighted within the 1987 Single European Act which states "*preventative action is to be preferred to remedial measures*" and again in several subsequent decisions and policies, these activities are outside the scope of this work. Thus this section shall largely concentrate on how the plastics that are at present and shall inevitably continue for the foreseeable future to arise from the waste streams detailed in section 2 are dealt with as per the EU's current position.

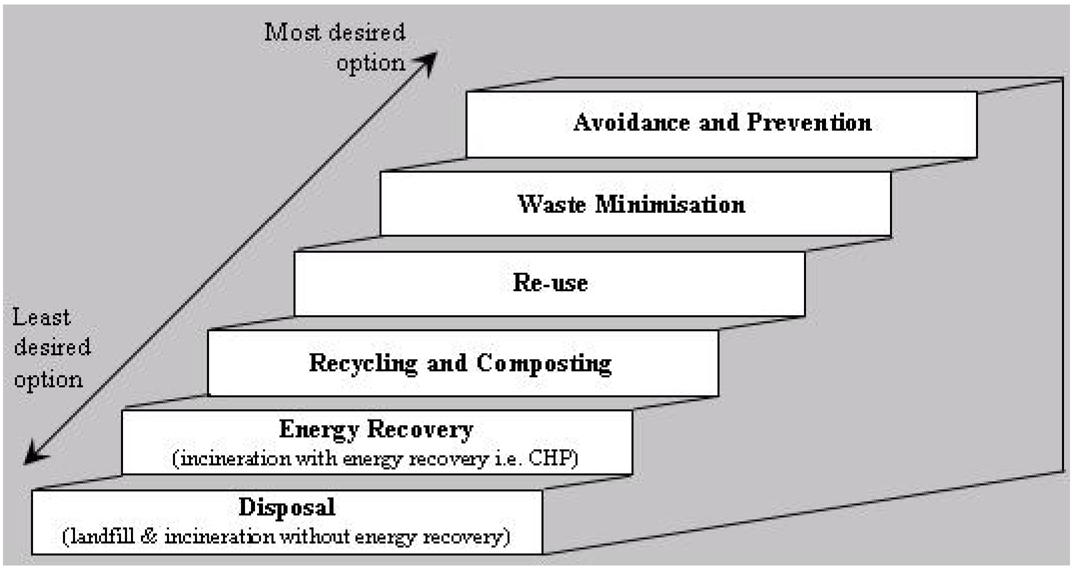

Figure 13: The EU waste hierarchy (adapted from Williams, 2005)

5.2 EU Directives and policy intervention relating to plastics waste

In order for public policy to justifiably intervene within a market based economy traditional economic theory requires that two general prerequisites should exist: 1) a failure in the market ('market failure') must exist in which market mechanisms and firms alone fail to achieve socially defined objectives; and 2) the state and its agencies must also have the ability to solve or mitigate the identified failure(s) (Edquist, 2001). Within the process of intervening into the market failure (or problem) a comparison between the existing situation and an ideal or optimal situation must be made so as to identify the gaps between the two and the best course of action to take in order to resolve the problem. The general problems with plastics waste have been introduced in previous sections as a loss of resources and source of environmental pollution due to unsustainable production and consumption and disposal practices, which have not been fully resolved by market forces alone. The waste management hierarchy in this case provides an indication of the perceived ideal situation and goal that society should strive towards.

In the last thirty years, the EU has developed comprehensive strategies and policy measures across a wide range of environmental issues and problems identified within the EAPs. In order to promote the principles and aims of the EAPs including the EU waste strategy the waste policies have been introduced through Directives, Regulations and Decisions establishing harmonised targets and stipulations which European Economic Agreement (EEA) countries are required to transpose into their national law/statutes. This harmonised approach has been adopted in order to establish coordinated action to solve common problems, and to ensure that the single market in Europe is based on common environmental standards (Gervais, 2002).

In light of the problems associated with waste production which, in the past and in the majority of cases today, is linked directly with economic growth, and with the problems relating to the landfilling of waste both in diminishing capacity, resource loss, health effects and pollution incidences the EU and individual countries by themselves have intervened in the system to encourage more resource efficient practices and internalize the external environmental costs associated with waste management.

The EU policy directives relating to plastics waste streams can be divided into the three main groups: **Horizontal/ Parent Directives** which aim to establish general framework for waste management including definitions and principles; **Treatment Directives/ Waste Management Operations** which relate to specific treatment methods including technical standards of operation; and **Waste Stream Specific Directives** identifies main waste streams and requires action to be taken on the collection, re-use, recycling and disposal of these specifically.

Three main EC Directives pertaining to specific waste streams now state a requirement for the recovery or recycling of materials which include plastics. These Directives, namely the 1994 Directive on Packaging and Packaging Waste (as amended in 2004), the 2000 Directive on End of Life Vehicles (ELV), and the 2003 Directive on Waste Electrical and Electronic Equipment (WEEE). These all state different requirements, however, there exists a general obligation for member states to recycle a proportion of the plastics emanating from these waste streams. A brief outline of the requirements stated within these directives as well as other directives that have influence on the end-of-life treatment of plastics and the potential impact they have shall be provided within the following subchapters.

5.2.1 Waste Framework Directive

The main parent directive covering solid waste in totality is the 1975 Directive on waste (waste framework directive) which was subsequently amended in 1991. This directive set out to define waste and establish general rules for the management of waste, which was defined within the original Directive as "*any substance or object listed in the Directive, which the holder discards or intends or is required to discard*". This definition has subsequently been updated with the development and introduction of the European Waste Catalogue in 1994 which provides a detailed list of which materials and practices are, and result in, waste. The Waste Framework Directive also stipulated requirements for each member state to produce an individual National Waste Strategy which includes the gathering of information relating to the type, quantity and origin of waste produced on a regional basis and the intended treatment routes and technologies identified for the processing of the waste generated. The emphasis is on establishing an integrated and sufficient network of disposal installations to enable the EU as a whole to become self-sufficient in waste treatment and disposal. The Directive also defines "recovery" in order to distinguish it from disposal (the landfilling and incineration without energy recovery among other similar activities which do not utilize waste resource potential).

This Directive remains the overall parent directive on waste management. Further amendments are currently being considered by the EU to cover further issues regarding several waste topics and issues. These include a revision on the definition of waste and when waste can be classified a resource and not 'waste'. This is being addressed in particular with Germany having classed refuse derived fuel (RDF) from Mechanical Biological Treatment (MBT a pre-treatment method for mixed MSW) which is being pushed as a fuel, not a waste in order that it may be combusted in conventional power plants not governed by the waste incineration Directive.

5.2.2 Treatment Directives

Directive on Landfill of waste

The 1999 Directive on the Landfill of Waste was introduced with the aim of harmonising landfill operations and practices throughout Europe and thus limit the damage to the environment (in particular to the ground water from leachate infiltration, and atmosphere through gas emissions) and to human health which may arise from the landfilling of waste. In order to achieve this, the directive places stringent demands on the licensing, construction criteria (geological and artificial liners), operation requirements (including waste acceptance criteria and reduction of biodegradables), monitoring, and end of life management (including financial security for remediation and restoration work) of new and existing landfill sites.

The Directive stipulates a requirement to have three distinctly separate sites for different waste classes covering Hazardous waste landfill, Non-hazardous waste landfill, and Inert waste landfill, (OJ L182, 1999). Pre-treatment of waste destined for landfill is stated within the directive as a prerequisite in order to reduce its volume, hazardous nature, aid its handling or enhance recovery. This applies to all wastes with the exception of inert or other where pre-treatment does not reduce the quantity or hazardous nature of the material (pre-treatment may include household source separation).

In order to reduce the activity within landfill sites in terms of leachate and landfill gas production, the directive stipulates the requirement to reduce biodegradable waste going to landfill (this directly affects biodegradable plastics). Table 2 outlines the required targets laid down in the directive with optional four year extended deadline for those member states that landfilled over 80% of their MSW in 1995 when the baseline levels are taken.

Table 2: Landfill Directive diversion targets for Biodegradable Municipal Waste from landfill (OJ L182, 1999 data)

Target (by weight)	**Deadline**	**Optional extended Deadline for member states landfilling over 80% of Municipal Solid Waste in 1995.**
Reduce landfilling of BMW to 75% of 1995 quantity produced	2006	2010
Reduce landfilling of BMW to 50% of 1995 quantity produced	2009	2013
Reduce landfilling of BMW to 35% of 1995 quantity produced	2016	2020

The outcome of this has seen a step up in landfill engineering and a subsequent increase in gate charges throughout Europe which has affected the industry as a whole. Firstly it has made alternatives to landfilling waste more economically attractive to waste collection companies and secondly has resulted in the closure of smaller landfills that can not compete or comply with new regulations, further promoting alternative means of treatment (Garrity, 2000). Through requirements for the diversion of BMW from landfills, composting and alternative treatment options for biodegradables are being established throughout Europe and therefore provide a system capable of accepting biodegradable biopolymer waste material (IBAW, 2005).

Based on the latest thematic strategy on the prevention and recycling of waste and communications from the Commission, further restrictions on the landfill of waste have been called for by the European Parliament. The proposals go beyond those of the 6th EAP and involve stipulations that the quantities of waste going to disposal are reduced to a minimum through the use of the most extensive ban possible on landfill of recoverable waste by 2025. Further time limits included in the proposal are that from 2015, an 80% ban on the landfill of plastics, rubber, metal, and paper among other recoverable wastes should be imposed. From 2020, a 90% ban on the landfill of all recoverable waste, and 90% ban on all residual waste except where unavoidable or hazardous (e.g. fly ash) by 2025 (ECOLAS-PIRA, 2005).

Integrated Pollution Prevention and Control (IPPC) and Incineration Directive

In 1996 the EU introduced the Directive on Integrated Pollution Prevention and Control with the overall objective of preventing or minimising the pollution to air, water, and soil caused by point source emissions from industrial facilities. The main requirement of the Directive is that certain categories of industrial installations must obtain a permit in order to operate. The system requires operators and regulators to take an integrated or holistic approach to the overall environmental performance of the facilities prior to issuing a permit which are to be based on the concept of Best Available Techniques (BAT). BAT is defined within the Directive as "*the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole*" (OJ L 257, 1996). In order to aid licensing authorities with the task of identifying which techniques are BAT, the European IPPC Bureau was established to co-ordinate an exchange of information between experts from the EU member states on the various industry sectors covered under the Directive (Europa, 2005).

The 2000 Directive on the incineration of waste aims, in conjunction with the IPPC directive, to reduce as far as possible the negative impacts on the environment caused by the incineration and co-incineration (such as in cement kilns, steel or power plants etc.) of waste. This aim is pursued by setting strict operating conditions, technical requirements, and emission limits including operating temperatures, treatment of ash and residues, and flue gas cleaning standards for incineration and co-incineration plants throughout the European Community (OJ L332, 2000). The Directive addresses several types of pollutants and aims to reduce levels substantially. Limits have been set for the emission of: total dust, Total Organic Carbon, HCl, HF, CO, SO_2, NO_x, heavy metals, and harmful dioxins and furans, for which the incineration of non hazardous waste has been identified as the major source of release into the atmosphere in past years (Williams, 2005).

Emission level values introduced by EU Directives on incineration and integrated pollution prevention and control have aided the enforcement of reduced air pollution from incineration practices, however the residues and effluent containing potentially hazardous substances are still required to be dealt with by other means.

5.2.3 Packaging and packaging waste directive

At the European level the only piece of legislation which currently explicitly refers to the recycling of plastics is the 1994 Council Directive 94/62/EC (amended in 2004 by Directive 2004/12/EC) on Packaging and Packaging Waste (OJ L47, 2004). As a result of the fact that packaging is inherently short lived due to reasons previously mentioned and the fact that it constitutes a large proportion of waste arising from our society, the European Commission, introduced the Packaging and Packaging Waste Directive in 1994[***]. This Directive covers the major forms of packaging and packaging materials with the overall aims of harmonising the national measures implemented by member states in order to minimise the impact of packaging and packaging waste on the environment. It also strives to ensure the function of internal markets allowing free trade throughout Europe without distorting or restricting competition (OJ L365, 1994). Within the directive there is no stipulation of how packaging collection, sorting and recycling/recovery should be financed and leaves this to the individual member states (i.e. producer responsibility is not a stipulated requirement) although most

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[***] after a previous attempt at regulating only liquid beverage containers in the 1980's was deemed ineffective due to different nations implementing different strategies which caused disparities across Europe in terms of effectiveness of harmonising the management of this specific packaging product,

countries (Denmark and the Netherlands being exceptions) have implemented such financing responsibilities.

The 1994 Directive defines packaging as *"all products made of any materials of any nature to be used for the containment, protection, handling, delivery and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer"* including non-returnable items used for the same purpose (OJ L365, 1994).

Leading up to the 2004 amendment, the consultation process and subsequent Commission proposal identified the possibility of distinguishing between different recycling methods giving mention to the following definitions:

"'Mechanical recycling' shall mean the reprocessing of waste material, for the original purpose or for other purposes excluding energy recovery or disposal, without changing the chemical structure of the processed material;

"'Chemical recycling' shall mean the reprocessing, other than organic recycling, of waste material, for the original purpose or for other purposes excluding energy recovery or disposal, by changing the chemical structure of the waste material and recycling the chemical constituents into the original material of the waste;

"'Feedstock recycling' shall mean the reprocessing, other than organic recycling, of waste material, for the original purpose or for other purposes excluding energy recovery or disposal, by changing the chemical structure of the waste material and recycling the chemical constituents into materials other than the original material of the waste." (COM, 2001b).

Mechanical and chemical recycling were seen by the commission as the more desirable methods for treating plastic waste arising from the packaging waste stream. Feedstock recycling was seen as less desirable, although still regarded as a complementary recycling option for recovering valuable resources from the waste stream. Due to the possibility of feedstock recycling being seen by industry as more attractive than mechanical or chemical recycling due to less pre-treatment requirements, and therefore competing with materials recycling for the available waste, it was proposed that targets be set for material recycling (explicitly stipulating chemical and mechanical) with feedstock recycling being a complementary recycling practice although only being included as an energy recovery option within the directives recycling target. However, these definitions did not enter the final directive due to ambiguity surrounding their definitions. Feedstock recycling is often used in reference to chemical recycling and industry (including PlasticsEurope) and academic researchers alike often do not distinguish between the two techniques. Therefore it was felt more general definitions of recycling and recovery were sufficient with the stipulation of a back to polymer recycling target (COM, 2001b; Hannequart, 2002).

Within the 2004 amendment the Directive makes direct mention and stipulates defined targets on the amount of plastic packaging arising to be recovered and recycled. The proposal, backed by external studies, stipulates that plastics recycling targets should be less than those set for other materials such as metals, glass and paper. This finding is a result of the technical limitations, disparities in the costs and benefits of recycling various materials compounded by difficulties in collection, sorting and establishment of end markets for recycled plastics. Therefore, differentiated targets have been set for the various packaging materials. A recycling target of 22.5% by weight of plastic packaging (counting exclusively material that is recycled back into plastics) is specified to be met no later than 31 December 2008 by member states. The general recovery targets have also been increased from 50% to 60% minimum of total packaging waste arising must be recovered (including incineration with energy recovery). The targets and years by which these are to be achieved are indicated in table 3.

Table 3: Packaging Directive targets by weight of material (OJ L47, 2004)

Recovery/ Recycling	**Target type**	**Deadline – Jun 2001**	**Deadline – Dec 2008**
Total Packaging Recovery	Min	50%	60%
	Max	65%	No upper limit
Total Packaging Recycling	Min	25%	55%
	Max	45%	80%
Plastics material Specific Recycling	Min	15%	22.5%

The final amended Directive defines recycling as "*the reprocessing in a production process of the waste materials for the original purpose or for other purposes including organic recycling but excluding energy recovery*"; energy recovery as meaning "*the use of combustible packaging waste as a means to generate energy through direct incineration with or without other waste but with recovery of the heat*"; and organic recycling as "*the aerobic (composting) or anaerobic (biomethanization) treatment, under controlled conditions and using micro-organisms, of the biodegradable parts of packaging waste, which produces stabilized organic residues or methane. Landfill shall not be considered a form of organic recycling*" (OJ L47, 2004)

Certain concessions are given to member states which have extenuating circumstances such as Greece, Ireland and Portugal and new member states. The targets set within the 2004 Directive are also due to be revised with new fixed targets for 2009 – 2014 by the end of 2007.

The Directive also defines requirements for packaging to be considered recoverable by composting only if it meets the European standard for compostable packaging, BS EN 13432, 2000, which sets out binding criteria for what can be classified as biodegradable. The fact that certain 'degradable' PE materials do not fall under the criteria set by the standard and are therefore not given an accredited compostable product label has resulted in moves being made by the oil-based plastic manufacturers to have the criteria changed to include materials that degrade through oxidation. Such proposals are being disputed by a number of composting associations and bio-polymer producers on the grounds that inclusion of such materials may decrease the quality of the compost produced and confuse consumers on what is compostable and what is not. At present however, only materials that meet the criteria and biodegrade through hydrolysis, leaving no toxic residues (verified by a third party) may be eligible for a recognised compostable accreditation (ENDS, 2004b; Murphy and Bartle, 2004).

5.2.4 End of Life Vehicles directive

Council directive 2000/53/EC on ELV which entered into force in October 2000 is aimed at minimising the environmental impact from the disposal of the 8 – 9 million tonnes that are generated each year. Although not stipulating specific targets for the recycling of plastics, this directive does state as an objective that "*recycling of all plastics from end-of life vehicles should be continuously improved*" targets indicated in Table 4. The directive also states that "*the development of markets for recycled materials should be encouraged*" and complements this by stating that an increasing quantity of recycled material should be integrated into new vehicles so as to help develop the markets for recycled materials. The removal of large plastic components such as bumpers, dashboards, fluid containers, etc prior to ELV shredding is also specified in order to promote recycling which is stated as being the preferred option over energy recovery when environmentally viable (OJ L269, 2000).

In terms of financing the collection, the ELV Directive introduces producer responsibility (see Appendix 7) stating that vehicles should be able to be delivered to an authorised treatment facility (which are required to meet stringent environmental treatment standards) without cost to the last owner (free of charge) by 2007. Further stating that the ‘Economic Operators’[†††] establish adequate systems for the collection of ELVs and producers are required to meet all, or a significant part of the costs associated with take back and treatment by 2007 (OJ L269, 2000).

Within the directive mention is also made to an examination of the environmental impacts of PVC, this study was underway when the directive was published in 2000 and suggested that proposals be made regarding the appropriate use of PVC within vehicles and else where in society. The findings of this report have since been published, the outcome of which shall be discussed in section 5.3. Restrictions on the use of heavy metals within new vehicles were also placed on manufacturers in 2003.

Table 4: ELV reuse/recycling/recovery targets by an average weight per vehicle and year (OJ L269, 2000)

	Vehicles produced prior to Jan 1980	**Vehicles produced since Jan 1980**	**All vehicles**
Deadline	Jan - 2006	Jan - 2006	Jan - 2015
Reuse & Recovery (minimum)	75%	85%	95%
Reuse & Recycling (minimum)	70%	80%	85%

Given that 9% of the average passenger vehicle weight in 2000 was plastics material and that this percentage continues to grow, the targets set by the directive for a minimum 85% of the average vehicle weight to be reused or recovery by 2006 (increasing to 95% by 2015) ought to promote more effective removal and treatment of ELV plastics waste arising. The directive also aims to influence the design and construction of vehicles to ease disassembly and encourage the use of recycled materials in the construction of new vehicles. This is influencing the entire life cycle of plastics utilized in vehicle manufacturing, from the design stage through to end of life management, an example is the introduction of new plastic materials that are more readily recyclable than existing composites largely utilized until now (ACORD, 2002)

5.2.5 Waste Electrical and Electronic Equipment directive

A Directive on Waste Electrical and Electronic Equipment (WEEE) was introduced in Europe in 2002 (2002/96/EC) and further amended in 2003 (2003/108/EC). This Directive, as with the ELV Directive, does not refer specifically to recycling plastics or set targets for this material flow. The directive does however set targets for specific categories of WEEE as illustrated in table 5. Definitions and examples of each equipment group are included within the directive, with medical equipment also being defined, however excluded from the requirements of the directive.

Table 5: Type of treatment by an average weight per appliance by 31st December 2006 (OJ, L37, 2003a)

Equipment groups	**Recovery**	**Reuse & recycling**
• Large household appliances	**80%**	**75%**

[†††] ‘Economic operators’ are defined within the directive as “producers, distributors, collectors, motor vehicle insurance companies, shredders, recoverers, recyclers and other treatment operators of end-of life vehicles, including their components and materials”.

- Automatic dispensers		
- IT & Telecommunications equipment - Consumer equipment	**75%**	**65%**
- Small household appliances - Lighting equipment - Portable Electrical and Electronic tools - Toys, leisure & sports equipment - Monitoring & control instruments	**70%**	**50%**

The WEEE directive, as with the ELV Directive, stipulates a requirement for producers' to be responsible for the financing of collection and treatment of waste arising which also aims to influence the design and production of EEE in order to enhance the ease of reusing and recycling their products. From August 2005 the Directive stipulates that the final holder and distributors of WEEE should be able to return such equipment free of charge by the availability and accessibility of collection facilities. These products should subsequently be transported, and treated at authorised treatment facilities conforming to appropriate environmental standards (OJ, L37, 2003a).

Along with the WEEE Directive, the European Commission produced a complementary Directive, the "Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS) Directive which came into force in February 2003. This Directive aims to ensure that, from July 2006, most (certain exceptions apply) new electrical and electronic equipment entering the market does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) which are known to have environmental and health burdens (OJ, L37, 2003b). As PBBs and PBDEs, (previously defined) are sources of dioxins and furans during melt recycling and other thermal treatments, and affect the material melt flow, this shall hopefully aid the recycling process for EEE plastics in the future, although today's waste plastics from older EEE shall continue to be present in the waste stream and require attention for some time.

5.2.6 Proposed Directive on the Biological treatment of Biological waste

A directive on the biological treatment of biological waste was originally proposed by the European Commission in 2000 in accordance with the priorities outlined within the 6th Environmental Action Programme. The original objective of the proposed directive was to stipulate mandatory requirements for the separate collection and treatment of biodegradable waste to compliment the EU Landfill directive stipulations of diverting biodegradables from landfill. The aim of the proposed directive was to establish rules on the safe use, recovery, recycling and disposal of biodegradable waste and control any potential contamination which could devalue and reduce the applications available for the resulting compost (OJ L273, 2002).

In February 2005 the European Commission announced that the proposed directive would most likely not be produced due to the opinion that issues regarding the composting of waste are or can be covered by national standards and legislation. The action surrounding biodegradable waste within the EC now appears to focus on the development of quality standards for compost and biologically treated biological waste to be introduced in an annex to the proposed revision of the waste framework directive (ENDS, 2005b). This may have potential impacts on the development of effective collection and composting plants for biodegradable polymers and the end market availability and acceptance of composted waste fractions.

5.2.7 Registration, Evaluation and Authorisation of Chemicals (REACH)

The EU's proposed regulatory framework for the assessment and control of chemical substances and their uses shall have an impact on the plastics industry in terms of what additives such as stabilizers and flame retardants can be utilized within plastic materials and certain applications. Within the proposal adopted by the European Commission in October 2003 which is currently being considered by the European Parliament and European Council, REACH (Registration, Evaluation and Authorisation of Chemicals) shall apply to enterprises that manufacture or import more than one tonne of chemical substances per year and would require the registration of such activities in a central European data base. The overall aim of the proposed new regulations is to update the existing legislations covering chemicals manufacturing and use within Europe which at present requires chemicals entering the market after 1981 to be tested for their hazard to human health and the environment but with no or limited control or identification and assessment of risk posed by chemicals existing on the market prior to 1981 as well as other identified weaknesses with the existing process of classification and monitoring.

Chemicals that shall be affected by this new framework regulation include the processing aids, stabilizers, flame retardants, compatabilizers, antimicrobials and other chemical additives utilized in the production of plastics (RAPRA, 2005). The plastics industry may be faced with the withdrawal of chemicals that are currently in common usage, and new, strict, testing regimes are likely to be required (BPF, 2005).

5.2.8 Transfrontier shipments of waste regulation

Following a number of cases in the 1970's and 80's of developed nations shipping hazardous waste for uncontrolled dumping in developing nations there became a need for tighter controls to monitor and restrict these operations, this gave rise to multilateral environmental agreements (MEAs). The first MEA to cover these issues was the 1989 Basel Convention (came into force in 1992), covering the control of transboundary movements of hazardous wastes and their disposal, followed by the 1992 OECD decision on the control of transfrontier movements of wastes destined for recovery operations.

Having introduced Directives relating to the Basel Convention in the 1980's, the EU, after the introduction of the OECD Decision produced a Regulation in 1993 covering these issues and replacing the previous Directives. This Council Regulation on the supervision and control of shipments of waste within, into and out of the European Community implements the requirements of the Basel Convention and OECD Decision on the EU member states (COM, 2003). Within the Regulation there are separate control regimes covering the imports, exports, transit shipments and shipments within the EU. Within these systems there are further rules and requirements depending on where the waste is destined, whether this is for recovery (and whether this is non-hazardous, semi-hazardous, or hazardous) or for disposal (waste arising within Europe is banned from being disposed off out with Europe).

For waste destined for recycling/ recovery the regulations distinguish between non-hazardous, semi-hazardous and hazardous through the classifying them into 'green', 'amber' and 'red' lists respectively as defined and listed within the annexes of the Directive. The Regulation requires that member states have a system whereby prior authorisation (prior written notification and consent) between the exporting, transiting and importing countries for the shipment of all waste for disposal and for amber and red listed wastes destined for recovery. A common, compulsory notification system and a standard consignment note for shipments of waste have been introduced for this purpose within the EU. It is the obligation of individual member states to take the necessary steps to inspect, sample and monitor waste shipments being shipped.

Plastics waste comes under the Green list which, provided they do not contain "*other materials to an extent which (a) increases the risks associated with the waste sufficiently to render it appropriate for inclusion in the amber or red lists, or (b) prevents the recovery of the waste in an environmentally sound manner*" (OJ 1993 L030/1) can be exported for recovery without the requirement for prior notification to the relevant national authorities. For countries not party to the OECD Decision, the individual countries involved can arrange an agreement for certain waste types, movements and recovery options, provided the provisions within the Waste Shipment regulations are adhered to and the EU informed. In these instances Green list waste come under normal commercial control as with OECD country transboundary shipments.

5.3 Polyvinylchloride (PVC) Green Paper

The use of Polyvinylchloride in various applications has been widely discussed for twenty years or more. Greenpeace have fronted a number of campaigns during these years to see an end to the widespread use of PVC and in particular the use of phthalate, cadmium, tributyl tin and lead additives commonly utilized within the material.

In 2000 the European Commission produced a Green Paper on the Environmental issues of PVC following the commitment presented within the ELV Directive to assess the impact of PVC on human health and the environment (COM, 2000). The paper identified and raised the main issues surrounding PVC use and waste management practices proposing a community wide strategy to reduce the environmental impact of PVC based on life cycle assessment findings and reports relating to recycling, landfilling and incineration of PVC. The commission also opened up the debate to member states, NGOs, industry groups and other interested parties (COM, 2000).

Largely in response to the issues surrounding the environmental impact of PVC, pressure from NGO's and the proposal for legislation by the EU, the PVC industry introduced and signed a voluntary commitment of its own in 2000 named vinyl2010. The commitment addresses the phase out of lead stabilizers by 2015 with a 50% reduction by 2010 as well as increasing post-consumer PVC recycling within Western Europe to 200 000 tonnes by 2010 (a reported 12 500 tonnes of recycling was carried out in 2004). Vinyl2010 also provide financial support to research and development in PVC recycling as well as subsidising collection of PVC material sent to certified recyclers (ENDS, 2005c).

Having produced the Green paper and received comments from the interest groups and proposals for statutory action on phasing out certain additives, the European Commission has decided that there are more pressing issues to consider and as yet no policies have been introduced from an EU level. The industry led voluntary approach, although not endorsed by the EC, has been seen as a viable alternative to political intervention at present, although the Commission is still proposing restrictions on phthalate plasticizers. Greenpeace have also moved their attention focus to the proposed REACH policy which is seen as a more important issue and has important implications on plastic additive use (ENDS, 2005c).

5.4 Summary of EU vision and surrounding issues

The emphasis of the EU waste management policies and strategies are directed towards minimisation of waste arising and of toxic or harmful nature of materials utilized. Thereafter, for the waste products that inevitably enter the various waste streams there is the hierarchical approach for waste management options desired to be utilized with material recycling back to the same material being the preferred option where environmentally viable. The clear ambition and goal of the EU emanating from the EAPs is to maximise resource efficiency and minimise materials going to final disposal through the introduction of statutory targets and improvements in waste treatment facilities and practices.

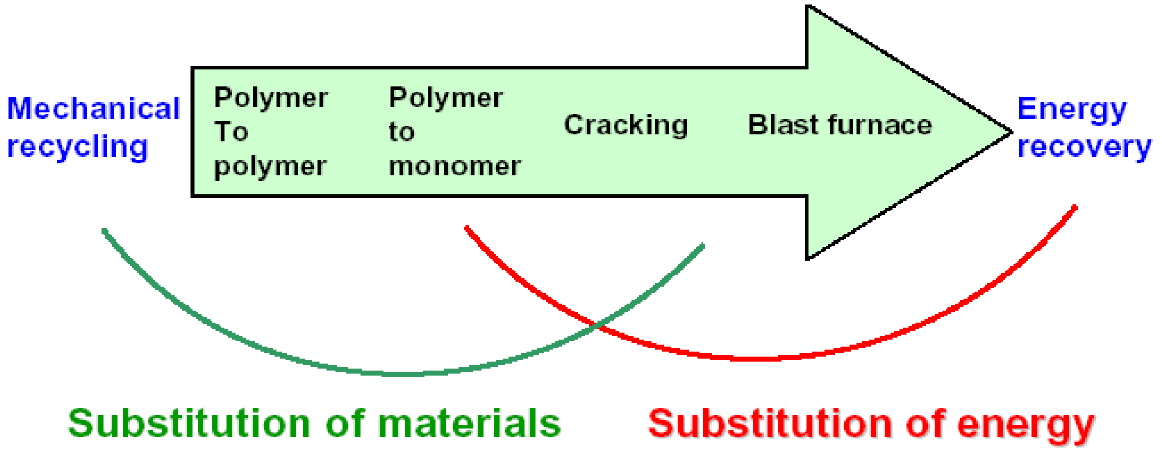

Figure 14: Recycling to recovery: a continuum of processes (EU, 2005)

Although the European Union stipulates requirements for recycling and recovery, the actual definitions of such are relatively generic. In March 2005 the EU Waste Management Committee met in Brussels to discuss informally issues and 'grey areas' arising from questionnaires sent to interest groups throughout Europe and the communication from the commission entitled "Towards a thematic strategy on the prevention and recycling of waste" published 2003 including a proposed revision of the Waste Framework Directive. The consensus within the meeting was that the general definition of recycling and recovery, which is often used interchangeably, was vague and insufficient. In terms of plastics recycling the committee appreciated that there is a continuum of processes available (Figure 14) as well as stating that there is no clear consensus or direction on where the clear differences in environmental benefits lie (Cooper, 2005).

6. Current Western European situation

This section aims to provide an overview of the plastics waste collection and treatment operations occurring throughout Western Europe and the developments that are taking place at present. Waste management systems are moving away from a reliance on landfilling of all commingled waste, to a more complex system which integrates the utilisation of various collection, separation, treatment and end market developments and techniques. When constructing and implementing a waste management system it is of great importance to focus on the whole chain of events so as to achieve the optimal system for the region and the waste stream. Issues surrounding the management of plastics waste are therefore interrelated throughout the whole system, with aspects of collection influencing treatment type, end markets and demand for materials influencing collection and separation. Therefore the results of discussions with various actors and other information sources from the plastics material cycle are presented forthwith in a structure that represents the waste material flow, however, issues from different stages in the life cycle are intermingled with other stages where relevant.

6.1 Collection and separation

Collection of the different plastic waste materials arising within the various waste streams lies at the heart of the waste management system. Prior to any of the waste treatment or disposal options available the material requires collection. In the case of recycling and certain recovery techniques, whether through mechanical, chemical, feedstock recycling, mono-material combustion (plastic material only incineration) or composting, the materials are required to be separated from other materials present in the waste stream or product. Appendix 8 provides an overview of the various waste types arising in the different waste streams, the typical collection schemes utilized throughout Western Europe and the reclamation obligation required by the EU in collecting and treating these waste products.

Materials commingled with various other materials complicate the separation and collection process. The main driving force for the separate collection of recyclable materials from the various waste streams is reportedly national and EU legislative requirements including recycling targets, bans, limits and rising costs (through the introduction of taxes and treatment directives) of landfill. However, other driving forces are reported, market demand for post consumer/industrial plastics is growing globally, partly due to increased consumption of plastics material compounded by rising virgin material prices. These market forces in conjunction with innovation in the recycling industry have resulted in increased material quality and are stimulating demand for recyclate, as well as consumer acceptance of recycled materials in products (Schefte, pers comm., 2005; Olsson; pers comm., 2005; Simmons; pers comm., 2005).

Packaging Waste Collection and separation

Although not stipulated within the Packaging and packaging waste Directive as a direct requirement, most member states have introduced a take-back obligation EPR approach into their national statutes. Variances exist between how EPR schemes have been implemented within member states including national mandated recovery/recycling targets whether for plastics as a whole or for certain polymers (i.e. PET), the use of a deposit refund system, the allocation of responsibility along the supply chain, and the establishment of PROs (some of which are responsible for all packaging, others only for household/sales packaging or Trade and Industry/distribution packaging waste). Within the take-back obligation schemes the option exists to individually take responsibility or join an established central PRO that takes charge of co-ordinating investment of revenue obtained from fees levied on the weight of packaging put on the market by producers.

Within the UK, a unique market driven tradable permit approach was established under the 1997 Producer Responsibility Obligations (Packaging Waste) Regulation (following the introduction of a landfill tax in 1996). Within the system there is no single PRO that manages all (or the majority of) plastics recycling transactions. UK businesses (cost shared by manufacturers (raw materials) (6%), converters (9%), packer/fillers (37%) and retailers (48%)) can comply with regulations by contracting with compliance schemes (of which there are approximately 15 at present) or by contracting directly with recyclers/recovery operators. Collection and recycling of packaging materials is carried out by local authorities, waste management companies and material re-processors. For each tonne of packaging recycled or recovered, the final (accredited) reprocessor (domestic or abroad (exporter)) can produce Packaging Waste Recovery Notes (PRNs/ PRENs [export]) which obligated businesses must purchase in order to prove they have fulfilled their recycling obligations. The supply of PRNs depends on the amount of recycling that takes place for each packaging material and if there is a shortage of recycling being carried out then the price of the PRN increases thus aiming to encourage more collection and recycling to take place and therefore reduce the price of the PRN. The revenues from the PRNs are supposed to be invested in new waste collection, sorting and reprocessing capacity (Watts, Jones & Probert, 1999). However the varying prices of PRNs and uncertainty in the market for post consumer/industrial plastics material has been stated to affect willingness to invest in collection and recycling infrastructure throughout the UK (Ecolas-Pira, 2005).

Norway, Sweden, Denmark, Germany, and the Netherlands have introduced deposit refund systems for one way and refillable (recycled after 12 – 16 trips) PET beverage bottles and other countries have deposits on refillable PET bottles. These systems set requirements for the type of polymer and additives allowed to enter the market in such products and in turn secure a homogenous waste stream available for recycling. Return rates associated with such schemes are high in comparison with door-to-door kerbside collection with an 80% collection rate reported in 2004 in Sweden, 77% collection in 2003 in Norway (Returpack, 2005; Resirk, 2005). Within Switzerland the PRO, PET Recycling Switzerland (PRS) operates a targeted collection service for post consumer PET bottles. The Swiss National Statute includes an Ordinance on beverage containers which stipulates that 75% of all PET containers in circulation must be reclaimed (a mandatory deposit/refund system may be imposed if the target is not achieved by industry alone, industry, reportedly due to the logistical burden associated with deposit/refund, are keen to avoid this) (PRS, 2005). PRS achieve this at present through wide ranging information campaigns through various media aimed at the general public combined with strategically placed collection containers throughout the country, achieving the collection of 29,000 Tonnes in 1994 equating to 78% of PET beverage bottles entering the Swiss market (PRS, 2005).

PET specific collection, inevitably also collects polyolefins present in the form of bottle caps (mainly PP). These are relatively easily separated from the PET fraction after shredding through float separation as the olefins have uniquely different densities to the PET fraction.

Collection of plastic bottles remains the main targeted waste plastic product from MSW due to the relatively large volumes arising as a result of high consumption, and the limited number of polymers utilized in these materials (mainly PET and HDPE). However other dense plastic packagings are also often collected along with bottles in drop off collection points and door-to-door collection schemes where available and operating. The market for polymers other than PET and HDPE MSW plastics is fairly limited at present however and therefore only

HDPE and PET are collected to any significant degree throughout Europe at present (Johansson, pers comm., 2005).

Plastic film is also less widely collected from the municipal waste stream due to the lower weight to volume associated with this material (compared to dense plastic or other recyclables). The main source of post use packaging plastics comes from industrial distribution and agricultural plastic films. Collection schemes for these sources are expanding throughout Western Europe so as to meet recycling target obligations. Collection costs in operating a household source separation scheme can be expensive as plastic (high) volume to (low) weight ratio makes separate collection difficult especially in low population density areas (Olsson, pers comm., 2005; Simmons, pers comm., 2005; Schefte, pers comm., 2005). The general perception from stakeholders interviewed is that, as separate collection infrastructure develops for industrial and household plastics waste, costs reduce. More bailing facilities, improved consumer awareness and information all aid in increasing the quality and quantity of collected materials, making collection systems more efficient in terms of material collected. Consistency and ease of understanding information on materials to be separated is however essential (Olssons, Simmons, Schefte, Quoden, pers comm., 2005).

Separation of mixed waste

In order to aid the identification and thus the separation, collection, and recycling process for the major thermoplastic polymer groups, the Society of the Plastics Industry (SPI) in America developed a series of symbols in 1989. These symbols, illustrated in table 6, have now been almost universally accepted. Although it is not a legal requirement within the EU to mark plastic products with such symbols, a 1997 European Commission decision issued a voluntary identification system for packaging materials covering the same six polymer types with numbers 7 – 19 being left undesignated for future use and a number of further codes for composite materials. Although there are many more plastic resin types than the six given specific codes, a committee at SPI decided on the seven symbols as these indicate the six major plastics that can be recycled and the "other" criteria is generic for the rest.

Table 6: Major thermoplastic recycling symbols and associated polymer type, density and melting point (Hocking, 1998)

Code symbol	**Plastic type/name**	**Acronym**
♳	Polyethylene Terephthalate	PET
♴	High Density Polyethylene	HDPE
♵	Polyvinylchloride (PVC)	V
♶	Low Density Polyethylene	LDPE
♷	Polypropylene	PP
♸	Polystyrene	PS
♹	All other resins	OTHER

Separation of MSW mainly takes place in centralized Material Recovery Facilities (MRFs) either manually or through the use of automated separation technologies. Material identification codes aid the manual separation of various common thermoplastic materials. However, labour costs are increasing throughout Europe and this process is labour, and therefore cost intensive. There are benefits to both automated separation and manual separation. Where HDPE and PET beverage bottles are the only plastics collected (these remain the predominant plastics collected in UK collection schemes), manual separation is relatively simple and sorting rates of 200 to 300 kg/person/hr can be achieved (Simmons, pers comm., 2005). However as collection schemes develop and more materials and products enter the system, sorting problems are significantly compounded and the collection of a variety of shapes, sizes and colours of material results in a decrease in both rate and quality of reclaimed material through manual separation. In addition, because turnover is high among sorting line workers consistency is difficult to achieve. Therefore manual separation rates are now reportedly in the region of 100kg/person/hour (Simmons *et al.*, 2003) where as automated separation can achieve (depending on system and through put rate) 1.5 – 10 Tonnes/machine/hour (Titech, 2005).

Automated systems can work on analysing the specific polymer(s) present in the material and therefore are not reliant upon markings (which may be on labels that have been removed, or on imprinted identification symbols which may be wrong (this can occur when processors change the polymer used without changing the mould in which the identification symbol is present)). This is also useful in the identification and separation of bioplastic polymers as these require to be reclaimed from the mixed thermoplastic material stream to avoid adverse degradation occurring upon melt recycling. This is particularly relevant in the case of PLA bottles which are entering the market and to the eye resemble PET bottles due to the texture and processing method. Automated systems have also been reported as beneficial as they allow for greater compression of mixed recyclable waste during collection due to higher speed sorting in recovery facilities thereby potentially reducing collection costs by up to 30% (Wollney *et al.*, 2002). However automated separation equipment can have high capital investment costs reported to be anything from £10,000 (€15,000) for one machine and £250,000 (€360,000) - £750,000 (€1.1 Million) to equip a fully automated MRF with multi-polymer separation systems (Titech, 2005; Eyre, 1999; Schefte, pers comm., 2005; Simmons, pers comm., 2005).

Within the UK Andrew Simmons of RECOUP stated that the majority of separation of packaging waste from both Trade and Industry and Households is carried out by manual hand separation in MRFs. The costs associated with this vary depending on the type of materials collected, however costs for separating plastic bottles from kerbside collection schemes are estimated to be in the region of £150-250 (€220-370)/tonne and for waste plastic packaging material from Trade and Industry (which is less contaminated, contain fewer polymers, and separated to a higher degree at source) in the region of £60 (€90)/tonne. Plarebel in Belgium state that average separation costs of household Plastic bottles, Metal packaging and Beverage cartons (PMB) fractions is in the region of £130 (€187)/tonne in 2003 (Plarebel, 2004).

The economic viability and therefore the commercial feasibility of separation technologies is very dependent upon the market price of the reclaimed material (which influences the pay back period for investment) compared to the market price for mixed waste (requiring little separation). The price associated with virgin PET, which has historically been the highest priced large-volume thermoplastic, has provided an incentive for the installation of automated systems to obtain a high homogenous quality from mixed polymer waste (Hulse, 2000). However, other high volume thermoplastics, due to virgin material costs being traditionally low, have not been so widely established to date.

Within MRFs, manual separation of materials remains the most widely applied technique and plays an important role in separating the larger easier identifiable material and polymer types as well as separating plastics from other material fractions (e.g. glass, paper, residual waste) where these are collected commingled. Recently developments and the commercialisation of automated separation technologies available to recycling facilities and MRFs have increased.

Commercially available automated separation equipment

Density/ specific gravity separation: Density is utilized in float-sink separation as previously described for polyolefin and PET separation. Varying densities of polymer types allow for the separation of polymers through the use of different mediums depending on the fraction(s) required to be separated. However certain polymers such as PET and PVC have very similar densities and therefore cannot be separated using conventional float-sink systems. In these cases froth flotation, which utilizes a combination of plastisers and surfactants to cause bubbles to attach to specific polymers, is required to make these polymers float in a liquid medium while similar density polymers sink (Schut, 2001). This is particularly of interest in the separation of automotive shredder residue for extracting metals, thermosets and thermoplastics (discussed later). Air blow separation is also based on separating lighter materials such as PE film from rigid fractions. The use of liquid mediums does present some issues in that materials have to be extensively dried prior to recycling due to the effect of steam produced in melt recycling if water is present producing bubbling in the recyclate (and where brine solution is utilized as the medium salt crystals must also be removed).

Near Infrared (NIR) spectroscopy detection systems: NIR is the most common automated separation technique utilized by the recycling industry throughout Europe which is capable of identifying the molecular structure of specific polymers and or other waste fractions including paper and composite cartons. Several systems have been developed, the first of which were single sensors capable of either identifying by single resin type or by colour from a single bottle width conveyer which required bottles to be fed one by one. Systems are now capable of a wider range of identification from a wider conveyer utilising single or multi frequency, multi channel sensors to identify a broader spectrum of materials and colours in a multi feed system (Kenny, Roe & Hottenstein, 1999). Identified materials are subsequently separated by compressed air jets located on the conveyer system. However NIR systems are limited in that they can not detect the polymer type of black and very dark pigmented plastics due to scattering and absorbing the infrared light as well as paints, coatings, or labels preventing the infrared light from reaching the polymer (Hulse, 2000).

Optical/image identification: Given the limitations associated with NIR in identifying certain coloured materials, visible light separation systems have been developed in order to enhance the performance and identify coloured and shaped materials (for example TiTech have developed an image identification system capable of identifying and removing PE silicon gun cartridge packaging as the silicon residue adversely affects material recycling) (TiTech, 2005).

Laser-induced breakdown spectroscopy (LIBS): This offers fast (less than a microsecond) identification of plastics based on atomic emission spectroscopy in which a laser is used to release excited ions and atoms from the material surface which can then be identified through spectral analysis to provide the elemental composition of the material (including polymer type and additives present) (Hulse, 2000). Other research and developments in the use of laser technology are also being carried out and entering commercialisation including Raman spectroscopy based on similar principles to that of LIBS.

X-ray fluorescence (XRF) spectroscopy: XRF identification systems were among the first commercially utilized automated separation systems in use. XRF is not capable of identifying specific polymers and instead relies upon identifying specific elements within the plastics material. XRF instruments can detect all elements heavier than sodium making it useful in identifying PVC due to the high chlorine content as well as identifying additives such as Brominated flame retardants, lead stabilizers etc. which may hinder the recycling of specific polymers from a number of sources. The main application of XRF has been in the separation of PVC from PET.

Electrostatic identification and separation: Separates plastic-from-plastic and/or plastic-from-metals. The separation occurs when two dissimilar non-conducting materials come into contact, charge is transferred and one of the particles becomes negatively charged and the other positively charged allowing separation to be undertaken. Although applicable in a number of sectors including packaging waste it is generally limited to separating only two material types and most commonly utilized in electrical cable recycling for separating the metal core from plastic sheath and PVC from PE in the plastic sheath recovered. However, with increasing interest and need to develop separation technologies for the WEEE and ELV sectors electrostatic identification is receiving a lot of attention. This technique is limited in that it requires a paint/coating free surface (Hamos, 2005).

Sliding Spark spectrometry: Similar to XRF in that it carries out elemental analysis although computer software interprets polymer type. Is unrestricted by coatings or colour and utilizes a electrical charge to vaporise the resin surface to accurately identify molecules present (Hulse, 2000).

A number of companies are currently producing identification and separation technologies for the European recycling industry. The most notable and widely utilized include TiTech Visionsort AS in Norway which have developed a range of polymer and colour sorting systems based on NIR and optical image identification with the latest equipment combining these two systems in order to maximise sorting effectiveness and efficiency. This equipment is in wide scale use within Germany where investment in automated separation equipment has been increasing along with collection. Some 400 TiTech NIR systems have been installed throughout Germany. The main polymers reclaimed include PVC, PET, PP, PE and PS as well as remaining mixed polymer fraction (separated from other materials commingled in the yellow bag household and drop-off collection systems) (TiTech, 2005). The investment in such equipment within the DSD system has reportedly brought costs down significantly as savings on labour costs have been achieved with payback time on automated systems typically being around 3-4years (Quoden, pers comm., 2005) Other facilities in Italy, Spain, France, Denmark, the UK and Belgium have also installed such equipment. Other companies including 'Magnetic Separation Systems' (MSS) of the USA; 'PELLENC selective technologies' of France; and 'Hamos GmbH' of Germany; among others, provide a number of technologies widely utilized throughout Europe including NIR, optical and XRF identification.

Most automated separation systems do require fairly substantial volume throughputs to make them economically viable. Within the Norwegian packaging waste collection system it has been stated that the volumes of waste both available and collected make the cost of installing automated separation technologies unviable, and therefore greater emphasis is placed on source separation within Norway. At present, where kerbside collection of plastic packaging waste is in operation, collection is carried out separately from other recyclable and residual wastes in large transparent bags. Plastics material delivered to MRFs located in Trondheim and Hamar (near Oslo), being semi automated, have the bags automatically split open, light plastic film is thereafter blown out by fans and goes through manual quality control and is mechanically recycled into new film either domestically or at other European recyclers with which Plastretur have contracts. Rigid bottles and trays are then separated by hand and due to the amount of rigid plastic collected (6-7000 tonnes/annum) and the number of polymers present, making manual separation timely and expensive (although not enough to warrant NIR or other automated systems), the majority of this fraction is shipped to Denmark. Large fully automated NIR identification and separation facilities exist in Denmark and are capable of separating the mixed waste into homogenous polymers providing a higher quality material for recycling and due to larger volume through-flows benefit from the economies of scale. The remaining items are collected including small fractions and contaminated waste not fit for mechanical recycling and is feedstock recycled at the German SVZ gasification plant (described in more detail later) (Shefte pers comm., 2005).

From Trade and Industry packaging in the form of pallets, crates and drums (PP & HDPE) and plastic film (mainly natural LDPE) continue to be readily collected throughout Western Europe. Given the size and often concentrated quantity of materials arising in this form automated separation is not usually required. These fractions offer relatively clean homogenous materials, however, in order to reduce collection and re-processing costs good source separation and information highlighting this fact, is required (Nordkvist, pers comm., 2005).

Other Municipal plastics waste

Other than packaging and WEEE, products containing plastics arising in municipal solid waste do not have stipulated recycling targets and due to their various sizes, polymer types and frequency of disposal often makes them undesirable for kerbside collection systems due to packaging being the main targeted waste.

The market price and demand for post consumer plastic materials (which is described in more detail in section 6.2) is currently high, and therefore some companies have reportedly attempted to collect other municipal plastic goods including garden furniture, children's toys, and other house wares in an attempt to increase the plastics available and the revenue gains associated with the sale of these materials. One such example has been reported by Nordvästra Skånes Renhållnings AB (NSR), Southern Sweden. NSR, which at the beginning of 2005 established a three month trial in the town of Anglehollm to collect all plastics from households in a door-to-door collection system. It was determined at the end of the trial period that although the collection of such products was not a substantial problem, the separation of the materials proved more problematic than anticipated due to being too difficult to separate out all the plastic products entering the Material Recovery Facility (hand separation), was too costly, and removed focus from concentrating on packaging waste which has the priority for recycling to meet targets (Jerslind, pers comm., 2005). The trial has therefore been stopped for the time being although this may be feasible in the future provided that market conditions for the materials recovered is high and associated costs in collection, separation and material sale can compete with energy recovery incineration (Fridh, pers comm., 2005).

However, certain recyclers throughout Europe do actively promote and accept household plastic products such as garden furniture (plant pots, patio tables and chairs etc), sledges, children's seats etc, if available in bulk (Davey, pers comm., 2005; Schnarr, pers comm., 2005).

Building, Construction and Agriculture

No European wide legislation exists stipulating collection or recycling targets for building and construction or Agricultural plastics waste. However, national policies and voluntary commitments do exist. Negotiations and consultations are currently being undertaken around draft regulations within the UK to introduce a statutory producer responsibility scheme for the collection and recovery of non-packaging agricultural plastics of which some 110 000 tonnes arises each year (ENDS, 2005c). Within other European countries especially Norway, Ireland, Switzerland, Germany and Spain where voluntary commitments are in place, agricultural film is already extensively reclaimed, recovered and recycled. Within the Netherlands there exists regulatory producer responsibility to reclaim plastic films from agriculture and voluntary agreements for PVC used in piping and exterior building materials. Other countries such as Denmark are also establishing systems to take back and recover PVC piping other applications. However the separate collection of plastics waste from building demolition is not wide spread and therefore limited amounts enter the recycling or recovery system.

ELV and WEEE

Collection systems for ELVs are relatively well established throughout Europe as traditionally, due to the market value for ferrous metals, which in the past have constituted in excess of 75% of a cars weight, have been collected and recycled profitably. However, the management of hazardous components within vehicles and the recovery of plastic and other component parts have not been taken care of to the same degree as the large metal fractions in the past. The ELV directive brings in new requirements for a number of European countries that have not previously regulated this practice and also brings in the producer responsibility concept in dealing with ELVs. Therefore, similar to the systems implemented by member states for the packaging Directive, PROs and individual producers' taking on the collection and treatment responsibility are developing a take back infrastructure in most member states at present.

WEEE equipment covering a wide range of products of various size and quantity is more complex to establish and ensure high rates of return given that many items at present enter the domestic commingled waste stream. However the potential for reuse is relatively high and markets exist for refurbished equipment providing an incentive and business opportunity in the sector (ICER, 2004). Collection schemes, although still to be established in many EU countries, are centring on take back schemes by retailers and community centralized drop off centres operated by either municipalities and funded through producers or operated by contracted firms.

Research and development of polymer identification and separation equipment for WEEE and ELV plastics has increased dramatically in recent years. Although partly associated with the recycling requirements of the respective EU Directives the developments can also be attributed to the resins utilized, which include high value engineering plastics such as ABS, SAN and Polycarbonates among others, which if reclaimed economically can offer cheaper materials for production of new products (Schut, 2001). Separation of plastic materials contained within WEEE and ELV products can be broken down into two main groups: large plastic fractions which are relatively easily reclaimed by hand; and remaining plastics which are present within the product when shredded, resulting in shredder residue.

In order to aid the efficient disassembly and recovery of component parts from ELVs, the major automotive manufacturers have collaborated in developing a software tool named IDIS (International Dismantling Information System). This system identifies materials, methods, and tools utilized in the construction of vehicles so as to aid the reverse, disassembly and enhance the collection of specific component parts. Hand held identification tools are also commercially available based on sliding park and electrostatic spectrometry including the tribopen, a small hand held unit capable of distinguishing between two different plastics (e.g. PVC and PP, PP and ABS etc) developed by Ford and the University of Southampton and now in commercial use throughout Europe (costs in the region of £800 (€1180) for a single pen (2003 price)) (Hearn, 2003). Painted surfaces of large components such as bumpers are increasingly being removed by mechanical abrasive techniques although chemical strippers are still employed by some re-processors (SMMT, 2005).

Given the wider use and range of additives utilized in the EEE and automotive sectors there has been a greater requirement to develop equipment that can identify the type and quantity of various elements within the waste to enhance the quality of recyclate produced. A number of larger handheld identification technologies are available to and utilized within the ELV and WEEE disassembly operations based on sliding spark, electrostatic technologies and XRF alone or combined with NIR for identifying the composition of resins from larger parts. WRAP UK is also funding the development of a recycling process for brominated WEEE plastics which are problematic and pose significant environmental risks when mechanically recycled. It has been determined so far that through the use of XRF bromine containing materials can be identified and subsequently subjected to a solvent removal process which enables the extraction and recovery of bromine and allowing the bromine free plastic to be recycled (Davidson, 2005).

Having obtained the easily identifiable and removable component large WEEE and ELV products are commonly shredded together in recycling facilities and therefore have similar issues to overcome. Table 7 provides examples of the materials arising from two European shredder facilities and an indication of the polymer groups present (Carpenter & Daniels, 2004).

Table 7: Automotive Shredder Residue fraction breakdown (Carpenter & Daniels, 2004)

a)

Materials	Sample 1	Sample 2
Fines	18.0	4.9
Residual metals	3.0	6.4
Foam	36.8	31.6
Wood	0.4	3.2
Rubber	17.3	22.5
Stone, fiber, other	10.1	0.0
Plastics	14.4	31.4

b)

Plastics	Sample 1	Sample 2
PP	41.4	31.9
PE	3.7	17.3
HIPS	4.9	3.3
ABS	8.8	11.5
PA	11.8	2.1
PVC	0.7	10.4
Rigid Urethane	18.9	13.4
PC/PBT	6.6	4.2
Other	3.2	5.9

Due to the wider use of thermosets in the automotive and EEE industries in comparison with other plastics sectors there is a requirement to separate non-polymer materials from the shredder residues and either the specific polymer types into homogenous fractions (if high quality mechanical recycling is to be an option) or at a minimum, if mixed polymer fractions are to be reclaimed for mixed polymer mechanical recycling, the thermoset plastics are required to be separated from the thermoplastic fractions. Table 7a breaks down ASR into several constituent fractions (including foam (which is mainly Polyurethane), rubber (elastomer), and fines (which may include textile plastic fractions) and therefore could also be classified as plastics fractions) with Table 7b illustrating a further breakdown of the plastics fraction identified in 7a. Within the plastics fractions it is also important to note that the type and quantity of additives including stabilizers, flame retardants and pigments etc as well as paint coatings on the materials vary substantially which may also cause difficulties in recycling separated polymers as one homogenous fraction. Given the complexity of ASR this waste stream has traditionally been landfilled or incinerated after the removal of ferrous metals. However due to the introduction of recycling and recovery obligations stemming from policy intervention by the EU and individual member states, along with the increasing use of plastics within the automotive and EEE sectors, there is an increasing need to recover these materials in an economically and environmentally sound manner.

In a joint project between Volkswagen AG and SiCon GmbH a Shredder Residue separation system has been in development since 1999 for ELVs and WEEE. Through a variety of processes including density, magnetic, electrostatic and optical separation, 95% of the shredder residue can be recovered for further utilisation. In the first process shredder granulate (including hard plastics and rubber); Shredder fluff (including foam and textile fibres); and Shredder sand (including glass, oxidised iron and other heavy metals) are recovered. Electrostatic separation is then employed to separate thermoplastics from themosets and elastomers with the thermoplastics including PP, ABS and PE being recovered in quantities and purity that enable mechanical recycling (SiCon technology, 2005). A number of plants are currently being constructed including a 100 000 tonne capacity facility in Enns, Upper Austria, an 8 000 tonne/yr capacity plant at the Belgian Scrap Terminal NV near Antwerp, and a 100 000 tonne/yr capacity plant in the Netherlands by Auto Recycling Nederlands (ARN) (ARN, 2005; VW media, 2005). Electrostatic and froth flotation are also being trialled at a number of European facilities for separating ASR waste into recoverable fractions (Schut, 2001).

6.2 Recycling and Recovery issues and developments

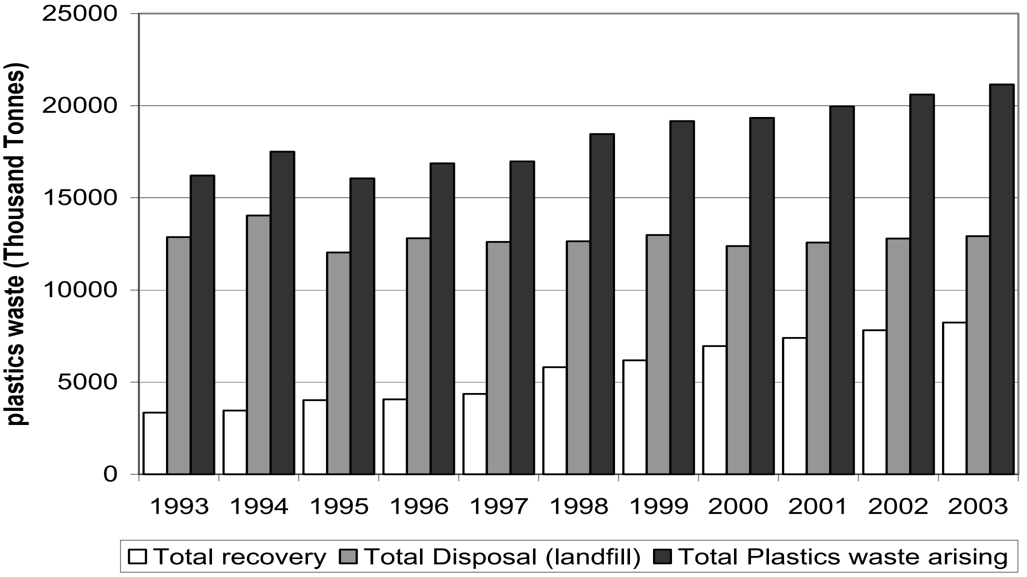

Figure 15: Management options utilized and total collectable plastics waste 1993-2003 (PlasticsEurope, 2004).

Figure 15 illustrates the trends in 'collectable' petrochemical plastic waste arising throughout Western Europe and the amounts going to landfill and that which is being recovered (including material/chemical/feedstock recycling and energy recovery (incineration and advanced recovery)) from 1993 to 2003 as reported by Plastics*Europe* (2004). This data indicates that the amount of waste going to landfill has remained relatively constant over the ten year period whilst plastics waste arising has increased and recovery options merely keeping pace with the increase in waste production. However, the latest European Commission's thematic strategy on waste prevention and recycling (which is currently in draft form and due to be published by the end of 2005) states that "The amount of plastic waste going to landfill has increased by 21.7% between 1990 and 2002, even though the percentage of plastic waste being landfilled has dropped from 77% to 62%" (Cartledge, 2005), although no further data or statistical evidence is available from the EU to confirm or expand upon this trend[‡‡]. It is evident that landfill remains the dominant option for plastics waste in Western Europe as a whole with PlasticsEurope (2004) stating that approximately 13 million tonnes being disposed off via this route in 2003 equating to 61% of the total 21 million tonnes collectable arising. However, recovery options are being increasingly utilized, figure 16 illustrates the trends in their use over the same ten year period (PlasticsEurope, 2004).

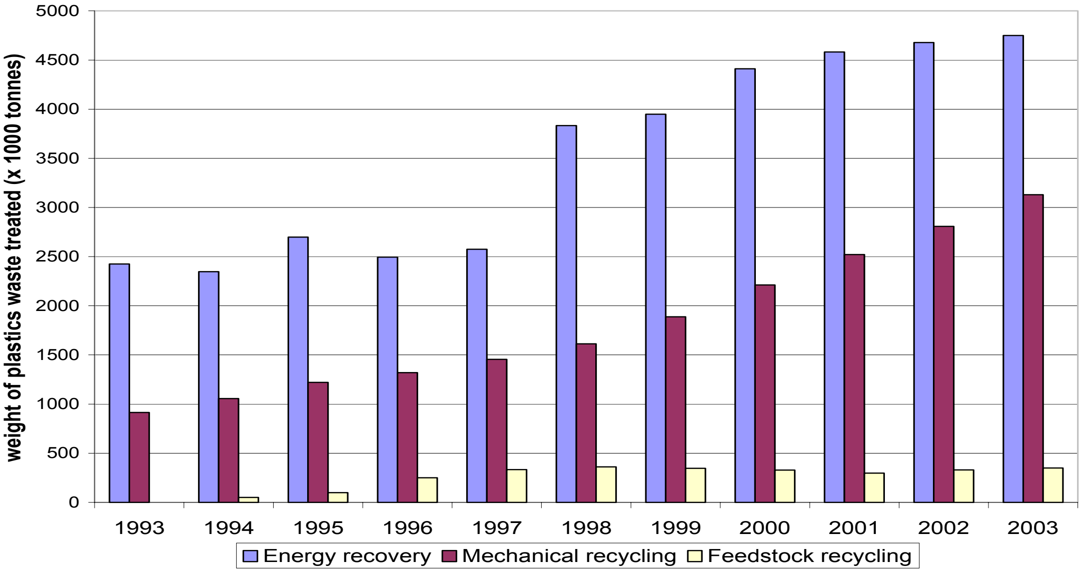

Figure 16: Recovery options utilized in Western Europe, 1993 - 2003 (PlasticsEurope, 2004)

Energy Recovery within Municipal Solid Waste Incineration plants is the main recovery option being employed throughout Western Europe as a whole. A large increase can be seen between 1997 and 1998 in the use of energy recovery, this is reportedly partly due to better data gathering in the waste management field throughout Europe, and partly attributable to a response to the packaging and packaging waste Directive and landfill Directive stipulations promoting further recovery, along with member state national waste strategy planning actions, drawn up in the early 90's, being developed and proposed incineration plants within the strategies coming on line (Johansson, pers comm., 2005).

Although Landfill remains dominant, a number of individual countries have developed recovery capacity and implemented individual strategies and policies in order to move away from direct disposal and utilize the resources available to a larger extent than other member states. Figure 17 illustrates the waste management options utilized by most individual Western European countries in 2002. Variances can be seen between each country with Denmark, the Netherlands, Norway and Switzerland utilising energy recovery incineration plants for a larger proportion of waste arising than other countries with over 60% of plastic resources being recovered in some form. There are political and social issues surrounding why energy from waste capacity is more prevalent in Northern European countries which shall be discussed in subsequent sections.

[‡‡] This may include carpets and textile plastics which are not included within PlasticEurope's findings however this can neither be confirmed nor disproved and therefore should be viewed with some caution.

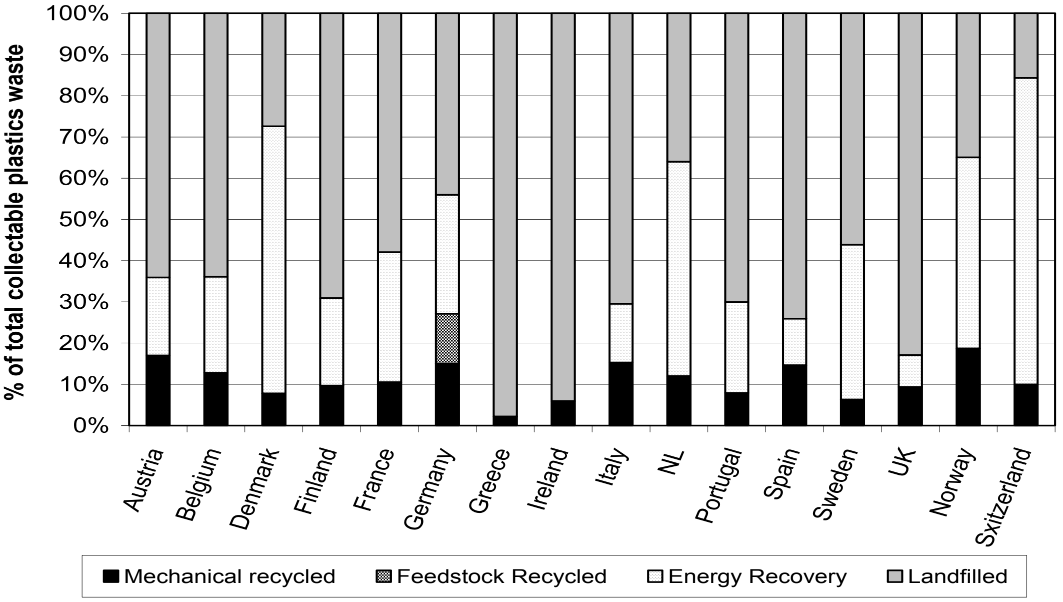

Figure 17: Management options as percentage of total collectable plastics waste per member state 2002 (PlasticsEurope, 2004).

Table 8 indicates the results of PlasticsEurope's findings on the waste treatment routes utilized by each end-use sector in 2002. Certain discrepancies may exist within this data and reuse does not enter the statistics which is relevant to Packaging, WEEE and ELV. Within the data presented for WEEE 2000 tonnes are unaccounted for. A survey conducted in the UK in 2003 by the UK Industry Council for Electronic Equipment Recycling (ICER, 2004) concluded that:

"*It is difficult to get reliable data on WEEE exports - amounts of equipment, number of operators, and value of this market. This is because export brokers have no incentive to give this information. However, [the] research estimates that there are around 30,000 tonnes per annum of waste domestic equipment being exported. …. In addition, some 133,000 tonnes of commercial equipment are exported, 23,000 tonnes of which are grey market or undeclared exports.*"

Table 8: Breakdown by recovery route and by end-use sector, Western Europe 2002 (x 1000 tonnes) (PlasticsEurope, 2004).

	Agriculture	Automotive	Building and Construction	Distribution and Industry	Electrical and Electronic	Municipal Solid Waste	TOTAL
Total available plastics waste collectable	311	959	628	4 190	848	13 671	20 607
Landfill and incineration (without energy recovery)	145	895	574	2 145	811	8 246	12 817
Energy recovery	1	7	0	444	3	4 222	4 678
Feedstock recycling	0	0	0	0	0	330	330
Mechanical recycling within Europe	149	58	52	1 332	32	843	2 466
Mechanical recycling for export	16	0	2	269	0	54	341
% total recovery as a proportion of end-use waste	53.40%	6.70%	8.60%	48.20%	4.10%	39.70%	37.90%

Although this equipment is exported for reuse and/or metal recycling there is some evidence to suggest that mechanical recycling of plastics was also carried out abroad in 2002 although it is suspected metal recycling is the primary interest and that plastics are often discarded in an environmentally unsound manner (ICER, 2004). The export of plastics from WEEE and other waste streams, especially packaging, for mechanical recycling out side of Western Europe is increasing and shall be described later within this chapter.

As illustrated in table 8, agricultural plastics undergo the highest mechanical recycling rate. This is predominantly achieved in areas where plastics use is high, particularly in regions of the Netherlands, Spain and France where the use of "polytunnels" to grow fruit crops is widely practiced. Due to the nature of agricultural plastics in these regions, high volumes become available for collection at the end of each season, allowing collection of a homogenous resin to be relatively practical and inexpensive.

6.2.1 Mechanical Recycling Developments and issues

Mechanical recycling capacity and demand from recyclers for post consumer waste has generally been increasing year on year for the past 15 years throughout the Western European region. With the industry being relatively young, techniques and technologies for processing plastics are continually developing. Advances and experience gained in blending techniques have aided the production of valuable recycled materials, as well as advances in processing equipment which can handle greater variances in melt flow index and the presence of certain contaminants than before (Nordkvist, pers. comm., 2005).

The financial viability of mechanical recycling post consumer waste is dependent on a number of factors including:

- Cost of obtaining waste (including the cost of collection/transportation and separation techniques).
- Energy prices and other production costs (including washing and removing contaminants present in materials obtained).
- Market demand and price obtainable from sale of resultant regranulate or product

Within the Western European recycling industry, the financial cost for mechanically recycling materials varies depending on the polymer type, source, contamination level etc. Approximate figures supplied by industries interviewed in Sweden, Norway and the UK indicate that the average cost (excluding collection and separation costs and the cost for sourcing materials) are in the range of €300 - €590/tonne (Williamson, Davey, Siglace, Schefte & Jerslind pers comm., 2005). Average costs for mechanical recycling of packaging plastics reported by DKR Germany have reportedly fallen from €400/tonne in 1996 to €260/tonne in 2003. These costs are falling as developments in techniques and increasing volumes are recycled are enabling the cost base to decrease.

It has been determined and illustrated previously that packaging is the largest source of plastic waste arising within Western Europe and within this food packaging represents approximately 50% (~7million tonnes) of the total packaging waste. Beverage bottles are also the most targeted plastic product in the municipal waste stream to be reclaimed and sent for recycling. However, the main reported barriers to closed loop recycling of food packaging are concerns surrounding the quality of the recyclate and the potential of contamination diffusing and migrating from the recycled resin into the foodstuff (Simmons, pers comm., 2005).

Food packaging legislation (EU Directive 2002/72/EC and amendment 2004/19/EC) requires that packaging materials must not cause the transfer and migration of any potentially harmful substances into the foodstuff (OJ, L71, 2004). Due to the fact that plastics materials commonly interact with chemicals in which they come in contact with, the diffusion of these chemical substances into and in turn out off plastics causes concern for the application of recycled materials in packaging as the potential for contaminants to enter the material throughout the previous life cycle and during reprocessing is high (Widén, Leufvén & Nielsen, 2005). A positive list exists within the EU plastic material for food contact Directive which is presently restricted to monomers and starting substances and incomplete list exists for additives as a harmonised evaluation is not yet finalized (Appendix 6 provides a more detailed overview of these issues). The food industry is therefore reluctant to utilize 100% recycled post consumer material in packaging coming into contact with foodstuffs unless analysis of the material can confirm and guarantee quality requirements.

Testing procedures of this nature are at present expensive and relatively unclear quality standards hinder further development of testing equipment. Due to the fact that the scale of recycling industries are predominantly small to medium sized companies (typically with a capacity of 5,000 to 20,000 tonnes per annum) this poses a substantial financial burden upon them if adequate guarantees and tests are to be given to the materials produced (Franz, 2002; Davey, pers comm., 2005; Jones, pers comm., 2005). However, from the large-volume of thermoplastics utilized in packaging material, PET has been determined to have low-diffusivity compared to other thermoplastics and hence has the highest potential for being closed loop recycled as well as being utilized as refillable bottle packaging (Jetten, de Kruijf & Castle, 1999).

Manufacturing processing techniques have been adopted to reduce the risk of contamination from migration. The use of functional barriers of virgin polymer materials between the recycled material and the foodstuffs has proven to successfully reduce contamination migration potential, however concerns surrounding this do remain (Franz, 2002). This technique is utilized in a number of applications including PP food trays, and PET bottles. At present the clear and light blue PET bottles collected from the Swedish deposit refund system are utilized in such a way (Returpack, 2005). The major food retailer in the UK, Marks & Spencer, is currently undertaking a six month trial in the use of recycled PET in their "Food-to-Go" range of fresh salads and juice packaging with a recycled material content of 30% – 50%. The trial has been set up in order to investigate consumer opinion and response to recycled content, to determine market opportunities for recycled material, and in response to previous research in the UK that suggests that the majority of consumers would feel 'more positive' about a brand or a manufacturer that uses recycled plastic (Jennings, pers comm., 2005; WRAP, 2005).

However, the issue of potential contamination or foodstuff quality distortion remains due to a guarantee that migration of contaminants is absolutely prevented can not always be made as a result of the lack of economically viable and well defined testing procedures. Therefore packaging producers appear to remain reluctant to use recycled plastics in food contact applications (Davey, pers. comm., 2005).

Bottle to Bottle recycling

As production and consumption of PET has grown, mainly in bottle applications, throughout Europe over recent years, so has collection and recycling. In 2002 some 449,000 tonnes of PET were collected for recycling growing 36% to ~612,000 tonnes in 2003 (Petcore, 2005).

Given the quality requirements associated with food and beverage packaging, more advanced technologies (than conventional mechanical recycling, although due to their nature are still classified as such) have been developed and are commercially operational achieving closed loop recycling of packaging materials. These have concentrated on PET bottles due to the low diffusivity of the material. The polymer structure of PET that enables chemical recycling to produce high quality constituent chemicals is also a possible recycling route for PET (Mishra, Zope and Goje, 2002). However this process incurs higher costs than mechanical recycling as the ethylene glycol and terephthalic acid recovered through chemical recycling requires being re-polymerised to obtain PET resin with related energy and equipment expenditure (Mishra *et al.*, 2002) (PET chemical recycling does however have advantages and is discussed later). Therefore in order to significantly reduce and effectively eliminate this risk and provide a pure grade recyclate comparable to virgin PET that meets criteria for food contact and in turn allowing for closed loop recycling of food and beverage PET packaging, an intensive cleaning process prior to mechanical recycling is desirable.

The Hybrid UnPET process developed by United Resource Recovery Corporation (URRC) in the USA in collaboration with the Coca Cola Company combines elements of saponification chemical recycling and mechanical recycling by way of utilising caustic soda as a 'chemical stripper' which removes only a predetermined percentage of the surface of PET flakes, and thus adhering residues as well as dissolving any PVC contaminants. Although the pigmentation within coloured PET is not removed by this process, optical sensors are used to remove these from the in stream which are then generally recycled into fibre products. The ethylene glycol and terephthalic acid arising from the stripping process can be precipitated out and recovered whilst the majority of flakes remain in PET resin form with high quality and purity. The process can accept slightly higher contamination than traditional mechanical recycling as the chemical stripping procedure washes out undesirable material. The PET bottles are ground to flakes along with labels, glues, and polyolefin caps. The pre-treatment steps remove the glues and labels and polyolefins are removed by float separation prior to obtaining highly homogenous PET flakes. These are then processed into a high-quality recyclate and can subsequently be used in a direct blend for producing new beverage bottles meeting industry requirements for purity and quality (Cleanaway, 2005).

Two such processes are in operation within Europe at present. One at the PRI (PET Recycling International) plant in Frauenfeld, Switzerland established in September 2000 utilising the clear and light blue fractions from the PRS targeted collection system and another at Rostock, Germany which utilizes PET bottles recovered from the deposit/refund and DSD systems, which began operating in 2002. Each has capacities to treat 15,000 tons of PET beverage bottles per annum. A third plant is currently proposed for construction in Norrköping, Sweden by Returpak in order to recycle the PET from the Deposit/refund system which are currently recycled into new bottles through the use of virgin material functional barriers, with some being exported to Germany for recycling at the Rostock plant (Cleanaway, 2005; Returpak, 2005).

A number of other technologies are also currently operating commercially as well as further innovative developments entering the market for the bottle to bottle, food contact approved recycling of PET bottles. The Austrian company Erema (Engineering Recycling Maschinen und Anlagen G.m.b.H) have also produced a PET recycling process which conforms to food contact requirements with operational plants in Austria and France recycling bottles to bottles as well as other food tray and blister pack products (Petnology, 2005). In 2003 approximately 11% of the total PET collected throughout Europe was purportedly recycled into new bottles equating to around 67,000 tonnes, an increase from 36,000 tonnes in 2002 indicating strong developments in closed loop recycling of PET packaging (PETCORE, 2005).

At present there are a limited number of viable processes capable of producing food grade polymers from post-consumer recyclate other than PET[§§§]. With the success of process developments in the PET market, a project aimed at developing a cost-effective process to produce food-contact approved HDPE (particularly milk containers) is being carried out within the UK. Particular attention is being placed on raw material source control, cleaning efficiency and analytical quality checks. The research objectives are to develop a process which can accept and safely recycle HDPE from all common UK collection systems (e.g. kerbside and centralized bring systems). Fulfilment of the requirements of EC Directives relating to plastic materials and articles intended to come into contact with food, and ensure the product is safe for use with regard to all other safety considerations, including being free from contaminants resulting from the unplanned use of the original HDPE container is the main challenge (Simmons, pers comm., 2005).

Mechanical recycling in other sectors

Markets exist and are developing in a number of sectors for recycled plastics material. Other packaging which does not come in direct contact with food stuffs does not have the stringent quality standards in terms of being acceptable for closed loop recycling. Plastics film from the distribution and agricultural sectors are increasingly being close loop recycled as clear LDPE packaging film can be obtained and recycled in relatively high quantities. In 2002 films and bags represented 30% of the products produced from recyclate within Western Europe (PlasticsEurope, 2005).

Although new processes are available for close loop recycling of PET, the main markets remain in down-cycling. The core market is in textile applications (mainly fleece and upholstery fabrics) which accounted for approximately 70% of the Western European PET recyclate market, and strapping and polyester sheet applications accounting for the majority of the remainder (Petcore, 2005). For example, of the 9,000 tonnes of PET collected within the UK in 2003 the vast majority was recycled into textile or strapping products (Recoup, 2005). Cooperation between countries to achieve economies of scale is being seen with PET from the Norwegian deposit/refund system mainly being recycled in Denmark in to food tray although textile applications were also a main end use in 2004 in Denmark (Resirk, 2005).

Developments in blending of two or more polymers are aiding the development of other viable markets for post consumer plastics. PET/PE blends provide high quality piping less brittle than PET alone and stiffer, better flowing and faster cooling than HDPE. The use of virgin PET for this application is economically unviable however the use of coloured PET bottle recyclate offers a viable polymer source. Currently three manufacturers produce industrial pipes from post consumer PET/PE polymers in Belgium, Spain and the UK (Schut, 2004). In 2002 pipes reportedly represented an estimated 12% of the market for all recyclate material use in Western Europe (PlasticsEurope, 2005).

PP from bumper and automotive battery applications are increasingly undergoing closed loop recycling as these are readily identifiable and removable containing limited amounts of additives. Ford UK for example utilizes 100% recycled PP (not exclusively from old battery casings) in all new batteries produced in the UK. However, although separation and re-processing technologies are improving and achieving higher quality recyclate, the main issue in the market development is that of colour. Mixed colour and mixed polymer regranulate often has a lower surface quality than virgin polymer and black pigments are required to mask the

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[§§§] See USA Food and Drug Administration for limitations and applications of these processes at: http://www.cfsan.fda.gov/~dms/opa-recy.html mix of colours present in the feed plastics. For this reason the majority of the markets in recycled coloured plastics are in hidden applications such as internal product parts, pipes, road furnishings (i.e. signs, noise dampeners etc), painted or coated products, synthetic wood and co-extruded polymers with recyclate acting as the core.

Based on literature sources and interview results the actual capacity within Western Europe for mechanical recycling of plastics in general appears to be 40% higher than actual recycling taking place. Recycling companies interviewed were all running at 50-70% capacity and all actively pursuing new feed material from the waste supplies. Markets therefore appear to exist for recycled material however obtaining high quality, homogenous, post consumer material at reasonable cost is the main barrier to utilising available capacity. In terms of individual polymers, capacity does vary; LDPE recycling is largest with PET and HDPE following closely and PP, PS, styrene co-polymers and PVC with lower capacity which is connected to collection volumes, technical limitations and market demand for material

Market price and demand for virgin, post use and recyclate thermoplastic

In relation to the price of virgin petrochemical plastics, recycled material is sold on the market at a discounted rate proportional to that of virgin materials in order to be competitive. The most commonly traded recycled plastics including PET, PE, PP etc are traded at 25-30% less than that of the virgin material before being considered for use by processors. Virgin petrochemical polymer prices, being largely dependent on the price of feedstock materials (i.e. crude oil and natural gas) which are traded on the global market, can vary dramatically over time due to a number of reasons. As mentioned in chapter 1, global geopolitical and environmental events have caused feedstock, and in turn polymer prices, to increase dramatically in recent years and months.

Table 9 illustrates exemplar costs for a number of virgin thermoplastics in the UK (indicative of European wide prices, bold figures indicate period average whilst bracketed figures indicate the high and low price during these periods). Although prices have varied considerably between these time periods, the general trend has been a price rise in all polymer resins. The major polymer producers including DuPont, Borealis and Dow have all been announcing price increases of around 50 – 70 Euros per tonne on all their thermoplastic resins in recent months with this price increase trend likely to continue throughout this year due to rising raw material costs (Omnexus, 2005; Polymertrack, 2005).

Table 9: Virgin polymer prices for 2002 (Jul-Dec) and 2005 (Jan – Aug) (£(GBP)/tonne) (polymertrack, 2005)

Polymer price (£)[****]	**HDPE**	**LDPE**	**LLDPE**	**PET**	**PP**	**PVC**	**ABS**	**PS**
Jul - Dec **2002**	**470** (425-510)	**505** (435-565)	**475** (410-530)	**650** (745-631)	**520** (490-630)	**450** (440-460)	**915** (900-920)	**575** (530-575)
Jan - Aug **2005**	**675** (570 - 770)	**750** (615-860	**730** (600-825)	**815** (760-900)	**695** (645-755)	**585** (530-640)	**1090** (1040-1110)	**805** (710-875)

[****] Prices are displayed as British Pounds Sterling per Metric Ton, and represent the lowest average contract price available providing a guide to the trend of resin prices. Individual prices are determined by volume, credit rating and a host of other factors and can therefore vary substantially.

Due to the increasing costs of polymers, many of the interviewees reported that there is increasing demand from plastic processors globally for recycled materials. This stimulates growth in viable market outlets for recyclate and draws more waste from the various streams as re-processors demand more and are paying more for the available waste. However, although plastic manufacturers are increasingly looking to recyclers for materials, there appears to be an information gap between recyclers and product manufacturers as to what quality can be guaranteed. It has been stated by a number of recyclers that there is an increasing number of plastic manufacturers approaching them with very high demands on what material, melt-flow-index and other criteria they require expecting to be able to obtain specific polymers in large quantities which recyclers, as yet, can not fulfil or guarantee (Davey, Nordkvist, Williamson, pers comm., 2005).

The food packaging industry is being affected by increasing virgin polymer material prices. Packaging can account for up to 10% of a food products cost, and at present plastics manufacturers are being increasingly constrained by high polymer prices and large retailers and food producers who pressure packaging manufacturers to keep their prices down. Therefore packaging manufacturers rather than companies that use plastic packaging are absorbing the price increases associated with raw material pricing trends. However it has been stated that plastics producers are no longer able to absorb the increasing costs. Such companies are not able to rely on productivity improvements alone to meet the demands of their customers and are beginning to pass along the cost increases to food processors and consumer goods companies. This appears to be having the effect of encouraging consumer goods companies to investigate and pursue alternatives to traditional plastics packaging and a number of companies are beginning to look at recycled plastics and bioplastics as alternatives to bring the cost base down or stabilize costs (Kiley, 2005; Davey, Siglace, Jones, Jennings, pers comm., 2005).

However, food packaging is a sector which is relatively localized as food and certain other product manufacturers do not want to ship empty packaging long distances and therefore the packaging industry is less vulnerable to outsourcing which is occurring in other sectors. Competition with foreign plastics manufacturers with lower cost bases is also influencing recyclate markets and the extent to which European plastic product manufacturers utilize recycled materials. It has been stated that due to cheap production and therefore cheaper goods entering the Western European market from foreign manufacturers, domestic processors increasingly need to make quality of product their competitive edge over imports. Therefore certain Western European manufacturers are reluctant to utilize recyclate in their products as the quality of material is not guaranteed and therefore acts as a barrier for domestic product manufacturers to use recycled plastics material as quality is their main selling point, and no recognised quality standards for recycled material exists at present (Bay, pers comm., 2005).

In relation to virgin polymer materials and associated price variances over time the prices obtained and paid for post consumer/industrial waste plastics also vary as illustrated in figures 19 and 20. The graphs provide an indication of the maximum price paid for material delivered to a UK merchant business which may send the plastics for recycling within the UK or export it. As post consumer/industrial plastics are traded on the international market these prices are indicative of European and global prices.

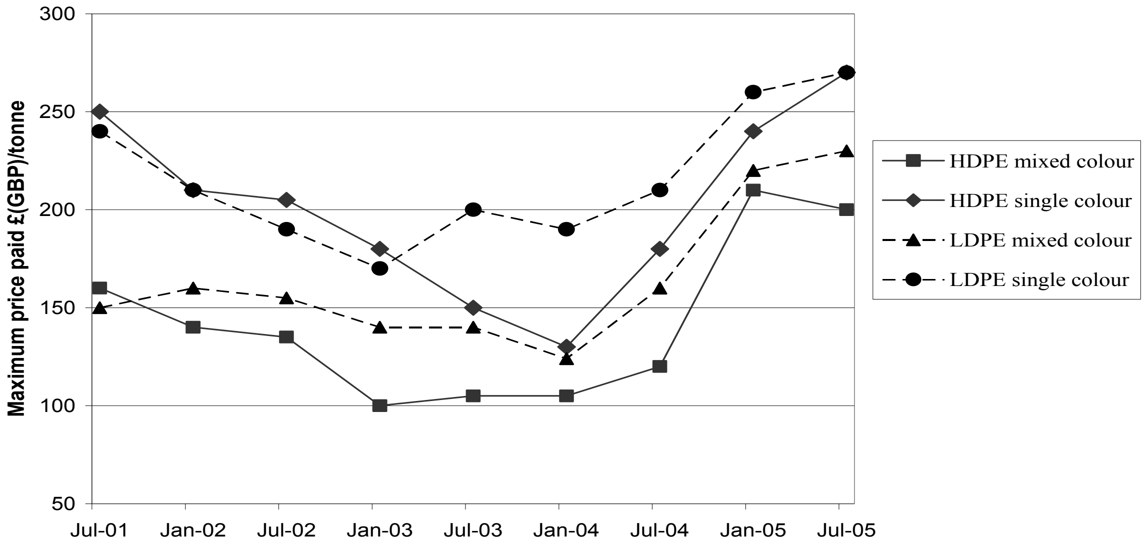

Figure 18: Plastic film Maximum price paid for post consumer waste UK (£/tonne) (letsrecycle.com, 2005)

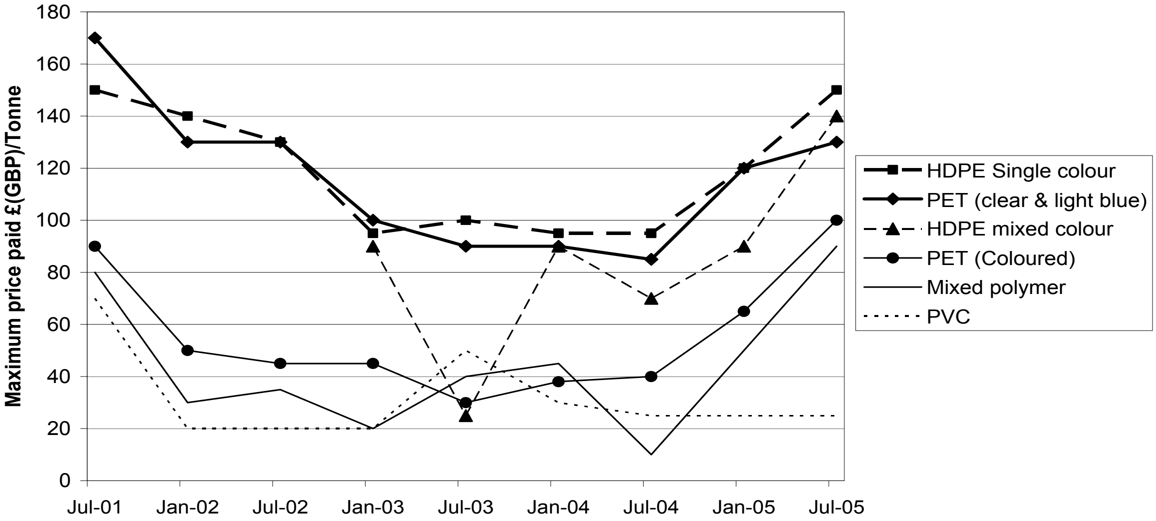

Figure 19: Plastic bottle Maximum price paid for post consumer waste UK (£/tonne) (letsrecycle.com, 2005)

Although the prices for post use plastics are related to virgin prime grade material prices, the main force reportedly driving the price increase since 2004 has been the demand for post use materials from non-Western European re-processors, in particular those in the Far East raising a number of issues which shall be explored forthwith.

International trade of post consumer plastics

The most pertinent factor affecting the recycling companies interviewed was the rising cost of post use plastics material with price increases which are reportedly mainly being driven by demand for post use plastics by foreign (in particular Chinese and Indian) recyclers driving the prices for materials above and beyond domestic re-processors' financial limit (Davey; Siglace; Williamson pers comm., 2005).

Due to rapid growth in technological and industrial development there is increasing demand for petroleum products including plastics in Pacific Rim countries such as China and India. This has caused a number of developments within the plastics sector, not only are these countries expanding their polymer production capacity, plastic manufacturing processing, export of both polymer material and plastic products, and domestic consumption of plastics material, but are also developing recycling capacity and technologies to recycle such waste into new goods. Lower processing costs (including lower, energy, construction, land, and labour costs for separating mixed polymer wastes) in these countries and demand for cheaper (compared to virgin) source of polymer material is high, and increasing (Duraiappah, Xin & Beukering, 1999). Under the transfrontier shipment of waste Regulation, mixed plastics waste (provided that it is not contaminated with non-plastics waste e.g. glass, paper etc) can be sent for reprocessing under normal commercial control, therefore no prior informed consent is required (Sutton, pers comm., 2005).

Relatively inexpensive shipping costs exist at present due to a net trade in goods from the Far East to Europe whereby containers returning to the Far East from Europe are either empty, or provided by shipping companies at low costs (this has been estimated to be around £300 (440 Euros) for a standard ISO 40 foot container from a European port to Hong Kong (Maersk, 2005)) making plastics waste export an economically attractive option.

Although homogenous waste obtains a higher price on the international market, as can be seen from figure 20, mixed plastics waste prices have been increasing rapidly since July 2004 and remain high at present (are subject to instability in this market and may fall). This is having an effect on separation practices within Europe as collection companies can obtain relatively high prices for mixed plastics without the need for investment in polymer specific separation practices (whether by hand or by automated systems). This has been noted by a number of Western European recyclers as a major barrier to further plastics recycling as exported mixed polymer waste can be manually separated into homogenous fractions in countries with low labour costs compared to European labour.

Of the 3.1 million tonnes of plastics waste arising in Western Europe mechanically recycled in 2003, it has been estimated that approximately 880 thousand tonnes (equating to 28% of the total mechanical recycling being carried out) was re-processed outside of Europe, mainly in Pacific Rim countries especially China. This is having an in impact on domestic recycling as figures presented for mechanical recycling within Western Europe fell from around 2.5 Million Tonnes in 2002 to 2.2 Million Tonnes in 2003. Therefore the total quantity of recycling in Western Europe fell by 300,000 tonnes between 2002 and 2003 (PlasticsEurope, 2005; Johanssen, pers comm., 2005).

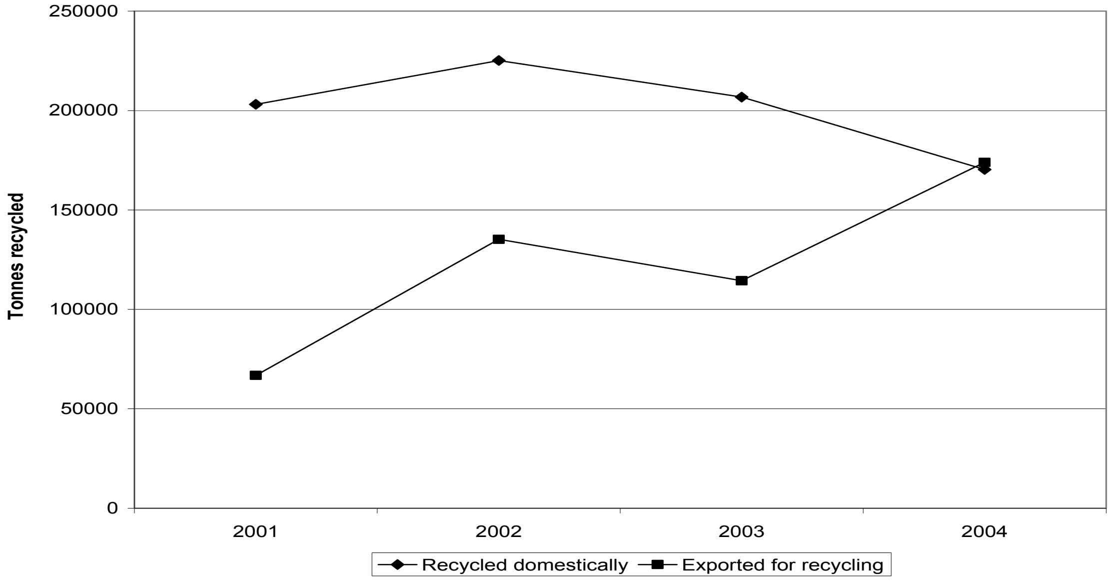

Figure 20: UK plastics packaging recycling domestic and export trends 2001-2004 (DEFRA, 2005)

Within the United Kingdom the effects of the export trade in plastics on domestic re-processors is observable within the plastics packaging data. Figure 20 illustrates the trends in domestic packaging recycling compared to export in material for recycling, with exports going to a number of Far Eastern countries (Defra, 2005). This may partly be attributed to the market based PRN approach adopted in the UK. Uncertainty surrounding PRN prices is affecting the willingness of collection, recovery and recycling organisations and industries to invest in new technologies, separation and collection equipment and infrastructure. The increase in export illustrated in figure 21 has lead to a significant reduction in plastic PRN/PREN prices with less revenue available to invest in new equipment and less desire to invest in separation equipment due to market demand for mixed waste. The collected material is therefore not of an adequate quality for domestic recyclers to accept or warrant paying high prices for the material collected and therefore export may inevitably increase (Williamson; Davey, Beattie pers comm., 2005).

Table 10 indicates the number of authorised recyclers within the UK in comparison to export companies between 1998 and 2005. Domestic re-processing facilities have fallen from 92 in 2001 to 65 in 2005 with accredited exporters increasing from 1 in 1998 to 46 in 2005. This trend within the UK is reportedly affected the ability of the domestic recyclers to broaden the market for their products as material can not be obtained to provide the critical mass required to promote and establish viable market outlets for recyclate (Davey, Williamson, pers comm., 2005).

Table 10: UK domestic re-processors and exporters accredited to issue PRNs and PERNs (DEFRA, 2005)

	1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Accredited domestic re-processors	71	66	83	92	88	78	69	65
Accredited exporters	1	12	12	30	42	41	39	46

This trend is not however limited to the UK, certain German, Dutch and Swedish recyclers have expressed similar concerns in stating that the plastics recycling industry throughout

Europe has seen a fall in re-processing/recycling companies and in capacity over recent years particularly for PP and PE recycling (Siglace; Quoden; Williamson; Davey pers comm., 2005).

Within Norway the collection companies processing plastic packaging PRO, Plastretur are obliged to sell to recyclers with which Plastretur have contracts. Although contracts exist with recyclers in Western Europe and Eastern Europe there are currently no contracts with recyclers further afield. Although collection companies can terminate contracts with the plastretur system and therefore sell material for the highest market price on the global market, it has been stated that collection companies consider this system more stable and in their interest in the long-term as a guaranteed market and rate of return is obtained (Shefte, pers comm., 2005). In 2005 the Swedish plastics packaging PRO Plastkretsen, having previously had a similar "closed" system to Norway's Plastretur opened up the market for plastic films to free market forces without long-term contracts. This reportedly resulted in a 50% increase in exports of plastic film between 2004 and 2005 due to higher market demand abroad. Plastkretsen are also planning on opening up the market to rigid plastics in the future (Olsson, pers comm., 2005). The Swedish Recycling Industries Association's Ulrika Idefjell (pers comm., 2005) also stated that "there is a lack of plastics waste for Swedish recyclers due to exports to the Far East", however she also stated that a number of large Swedish recycling companies are working in cooperation with Chinese firms enabling them to benefit from the viable market and lower costs in Asia.

Plastics waste is an internationally traded commodity and is subject to open market forces, therefore recycling companies have to be competitive as in any other market. However, although there are stringent restrictions placed on the export of waste by the TFS regulations, there is a significant proportion of trading in illegal and grey area exports from EU countries to Asia and other nations in direct violation of the regulation. In October 2005 the European Union's network for the Implementation and Enforcement of Environmental Law (IMPEL) carried out inspections of waste consignments in seventeen European ports destined for non-European countries. Of the 140 containers containing waste shipments, 68 were found to contain illegal consignments with violations detected primarily in France, Sweden, the UK and the Netherlands. Illegal shipments included containers found to contain mixed household waste (paper, plastics, metals etc in one consignment), WEEE containing CFCs, PCBs and unauthorised shipments of ELV and WEEE waste to non-OECD countries (IMPEL, 2005). As a result of previous inspection projects intercepting large numbers of illegal shipments and the observed inadequacies, a European enforcement strategy is being developed in order to police shipments more stringently (IMPEL, 2005). In March and April 2005 Dutch agencies also discovered vast quantities of mixed household waste, documented as being paper, in violation of the TFS regulations in containers in transit from European Countries and destined for Asia (ENDS, 2005e).

6.2.2 Advanced recovery technology developments

Advanced recovery technologies were first introduced for the use in treating plastics waste within Germany in the 1990's following the introduction of the German Packaging Ordinance in 1991. As collection of plastics increased, there was limited capacity to mechanically recycle the post consumer plastics, immature recycling technologies and difficulties in recycling due to the number of various polymers and limited separation techniques available. Therefore there was a rapid development in alternatives leading to a number of feedstock and other recycling and recovery processes entering into use (Fishbein, 1994; Wollny *et al.*, 2002). Much of the advanced recovery technologies utilized within Western Europe have remained almost exclusively within Germany until recently as a renewed interest and development of such processes has appeared.

Among the advanced recovery technologies developed and utilized in the 90's within Germany were the Veba Oel AG Combi Cracking (VCC) hydrogenation plant at Kohleol Anlage Bottrop and the Sekundärrohstoff-Verwertungs-Zentrum Schwarze Pumpe (SVZ) gasification methanolysis plant, with other pilot projects being trialled including the BASF thermolysis plant constructed in 1994 in Ludwigshafen which shall be described.

VCC and BASF plants, Germany

The Veba Combi Cracking process at KAB utilized an existing coal and crude oil distillation residue hydrogentation plant that produced synthetic oil and gas which were further processed in refineries (Wollny, *et al.*, 2002). In 1992/93 a depolymerization unit with a capacity of 90 000 tonnes/year was added in order to enable the use of mixed plastics waste in conjunction with the existing feedstocks. In 1998 some 87 000 tonnes of post use packaging from the DSD system were treated at this plant and tests were also performed in 1997 utilising some 50 tonnes of WEEE, these proved successful. However, having treated waste plastics from the DSD system from 1993, in 1999 DSD and Veba agreed to terminate the contract which was to run until 2003. Although reportedly no formal reason was given, high operational costs (unable to compete with the SVZ and blast furnace processes) and better separation and therefore more mechanical recycling taking place are believed to have made the process unviable (Wollney *et al.*, 2002; Tukker, *et al.*, 1999). Tukker *et al.*, (1999) estimate that the gate fee charged for the VCC process was in the region of €250/tonne prior to ceasing operations.

The chemical company BASF developed a feedstock recycling process for mixed plastic waste in the late 80's/early 90's based on pyrolysis and cracking to obtain a synthetic naphtha (which can subsequently be steam cracked to produce monomers for new plastic applications), synthetic gas, coke and char residue. In 1994 a 15 000 tonne/year pilot plant was constructed in Germany and proposed to construct a 300 000 tonne/year capacity plant following DSD's estimate that 750 000 tonnes of waste plastics would be available for feedstock recycling. However after DSD revised their figure in 1995 to 400 000 tonnes being available, BASF could not secure a long term contract with any plastics collection companies that were willing commit the volumes of plastic and pay a gate fee that would cover investment costs and the pilot plant was closed. Gate fees were reportedly expected to be around €250/tonne for the 150 000t/yr plant and €160/tonne for a 300 000 t/yr plant (prices as at 1996) (Tukker, *et al.*, 1999).

SVZ plant, Germany

The SVZ gasification plant in Germany started processing mixed plastics waste from DSD in 1994 and remains the largest and main feedstock recycling plant within Western Europe at present. Plastics from Norway, Austria and Denmark are now also processed at this plant. The process converts various waste materials including mixed plastics waste (from packaging, and WEEE and ELV shredder residue), Refuse Derived Fuel (RDF), wood, sewerage sludge and waste oils into syngas and methanol by gasification (Tukker *et al.*, 1999). The plant has a capacity to process approximately 550,000 tonnes of feedstock per annum split between 495,000 tonnes of solid waste and 55,000 tonnes of contaminated oil and oil-water emulsions. Plastics waste processing capacity is estimated to be around 150,000 tonnes per annum (Quoden, pers comm., 2005). The feed materials require pre-treatment including PVC removal (tolerated chlorine content of waste feed is around 2%), size reduction (20 – 80mm) and mixed with lignite coal. This is then fed into seven solid-bed air-blown gasifiers (15 tonne per day (tpd) capacity) and one British Gas-Lurgi (BSL) pure oxygen based gasifier (30tpd capacity). The syngas that is generated is then utilized in generators (a 44.5 MW gas turbine plus an additional 30 MW steam turbine (utilizing exhaust heat)) or the methanol plant (Valenti, 2000).

The process produces around 100,000 tons of liquid methanol per year for which applications include petrol additives, methylating agents in paint, ethanoic acid in wood preservatives and disinfectants, refrigerants for cooling systems, and solvents for resins and waxes (SVZ, 2005).

A considerable amount of investment has been made in developing the SZV plant from the original coal gasification plant to the present condition. Investment has been estimated to be in the region of €250 Million with further investment in developing and refining the BGL plant which began operation in 2000 and was granted a licence for continues operation in 2004 (SVZ, 2005). The plant has recently been sold to the Swiss company 'Sustec Industries AG' following insolvency and therefore no further information regarding operations could be obtained including current gate fees. However, Tukker *et al.*, (1999) state that the gate fee, although highly dependent upon the volume and time period of commitment to deliver waste to the plant, was around €150 (£100)/tonne or less for mixed plastic waste in 1999 and Wollney *et al.*, (2002) state a similar figure of €175/tonne.

As previously mentioned, packaging collected in Norway which is not suitable for mechanical recycling is sent for feedstock recycling at the SVZ plant. Although gate fees for incineration of this type of waste within Norway are lower than those of the SVZ plant, and transportation/ shipping costs are higher, the municipalities reportedly consider chemical/feedstock recycling preferable to incineration and based on an LCA conducted by STØ comparing treatment options, the SVZ plant has was indicated to be favourable to EfW incineration plants in Norway. The current recycling targets within Norway also require 30% of the plastics packaging waste arising to be recycled of which 7.5% (the difference between the EU packaging waste Directives 22.5% material recycling target and Norway's national 30% recycling target) can be chemical/feedstock recycled (Shefte, pers comm., 2005). In 2004 around 4 100 tonnes representing 4% of the total plastics packaging waste arising in Norway was recycled at the SVZ plant (Plastretur, 2005).

Blast furnace

Plastics are utilized in pig iron production where it acts as a carbon source replacing coal and heavy fuel oil as a reducing agent in the blast furnace. In this process waste plastic chips are fed into the blast furnace where at temperatures in excess of 2000^{o}C the plastics purportedly instantaneously gasify where the resultant synthesis gas reacts with and removes the oxygen from the iron ore (the reduction process) which is necessary in the manufacturing of pig iron. Although plastic resources are oxidised in this process, which would normally classify this process as incineration, the fact that they act as a reducing agent (partly oxidised by oxygen in the ambient air, and partly from the oxygen in the iron ore itself) this process is regarded as feedstock recycling, as it directly utilizes the chemical energy of waste in a production process (Wollney *et al.*, 2002; Sander *et al.*, 2004).

This process has been carried out since 1995 in Germany where around 100 thousand tonnes of mixed plastics (primarily packaging) waste too contaminated for mechanically recycle is utilized each year at the 'Bremer Stahlwerke' steel foundry (DKR, 2005). The Corus steel foundry in Ijmuiden, Netherlands is also currently proposing, and likely to be applying this technique. The Corus plant which is looking for a low chlorine replacement for coke and coal which is currently being utilized by the plant is expecting that 2 – 4 thousand tonnes of plastics waste screened to remove contaminants or products containing cellulose film, phosphorus, zinc, sulphur, ashes, and other heavy metals, with a further process to dechlorinate the material where after it is granulated and with the resultant material requiring to have a minimum calorific value of 28MJ/kg shall be treated in this way to produce Redop (Reduction of Iron Ore by Plastics) granules which have lower chlorine and sulphur content than the coke and coal in use at present saving on corrosion and pollution abatement costs (Lucas, 2005). The potential for further utilisation of plastic waste resources in similar processes is relatively unknown as this depends on availability and price competitiveness with alternative treatment capacities, availability of waste plastic resources in the vicinity of the steel foundries and willingness of these facilities to invest in pre-treatment and injection equipment. It has been estimated that the theoretical capacity of Blast Furnaces in Europe for accepting plastics waste is around 5 Million tonnes per annum, based on operational steel foundries (Tukker *et al.*, 1999).

The gate fees charged for plastics going to Blast furnaces has not been obtained however it is estimated to range from 0 to 100 €/tonne (depending on quality of waste and pre-treatment required) (Tukker *et al.*, 1999).

Other identified Advanced Recovery Technology utilisation

The Swedish plastics packaging PRO, Plast Kretsen are reportedly to begin utilising a feedstock recycling plant in Poland in 2006 for waste unsuitable for mechanical recycling. Following the ban on landfill of organic (combustible) waste in Sweden in January 2005, the quantity of waste going to energy recovery at municipal incinerators has increased. However, due to shortage of incineration capacity for the combustion and energy recovery of plastics waste there is a need to find alternatives to both landfill and incineration for fractions unsuitable (e.g. too contaminated) for mechanical recycling. Therefore feedstock recycling has been determined as a viable option and, as with Norway, has been determined to be environmentally preferable in terms of recovery efficiency and green house gas emission and shall also aid in achieving nationally set recycling targets (Olsson, pers comm., 2005). Further information regarding the type and location of feedstock recycling plant to be utilized in Poland was not available, nor were the quantities of plastics being proposed to be recovered by this means. As Poland is outside the geographical scope of this report no further information was obtained from other sources referring to the scale or type of plants available.

Although outside the scope of this paper, engineering plastics utilized in carpets are also being chemically recycled in Germany. Over 40% of the engineering polymers polyamide (PA) 6 and 66 produced are used to make carpets. In Europe, approximately 900,000 tonnes of carpet become waste each year, 70% of which are disposed off to landfill. Although mechanical recyling of these polymers is possible, the mixed colour and material degradation prevent their reuse in carpets. In 2000, the German company Polyamid 2000 began operating a 120,000 tonne/year PA depolymerization plant at Premnitz (near Berlin). The process identifies PA6, which is depolymerised to caprolactum (of 'virgin' quality) which is repolymerised to new PA6 for use in carpets, and PA66 which is mechanically recycled for use in car parts. Other materials present within the carpet waste are incinerated on site to provide heat and electricity for the facility. Due to the higher price associated with PA in comparison with commodity polymers this process has proven to be economical in operation (Jones, 2004).

6.2.2.1 Emerging Technologies

A substantial number of research and development projects have and are investigating feedstock and chemical recycling technologies (see Tukker *et al.*, 1999; and Williams *et al.*, 2003 for further examples). However those which are seen to be on the verge of commercialisation or have been identified in literature as being promising processes are presented forthwith.

PET Chemical recycling

The use of metallic alkalis in a saponification process (the hydrolysis of an ester under basic conditions to form an alcohol and the salt of the acid) has been proven for the chemical recycling of PET to isolate the two monomers, ethylene glycol and terephthalic acid (Mishra, Zope & Goje, 2002; Carta, Cao & D'Angeli, 2003). Given the limitations of mechanical recycling (including the Hybrid UnPet process) which are not capable of accepting coloured PET bottles, polymers being subjected to heat and shear degradation making more than approximately nine processing cycles largely impractical, and PET products containing barrier resins and other additives causing difficulties in producing high quality recyclate, chemical recycling is a viable alternative in the long term.

Therefore the PET and PTA (Purified Terephthalic Acid) producer 'Equipolymers' which has production facilities in Germany and Italy has reported that they are to build a 10,000 tonne/year capacity PET chemical recycling plant in Sardinia, Italy in 2006. The project is being supported by Corepla (the Italian packaging PRO) M&G, Clariant, Tecnimont and Ecosol. The process shall utilize PET bottles collected by Corepla and convert them to PTA and ethylene glycol fractions. These are proposed to be subsequently utilized in Equipolymers Italy PET manufacturing plant combined with virgin PTA to produce new PET resin suitable for food contact (Equipolymers, 2005; Reade, 2005).

A 15 thousand tonne/year chemical recycling plant has also been established and is reportedly operating trials in converting post consumer PET bottles into intermediates for polyols used in polyurethane foal manufacturing in France (Mayne, 2002). However no further details on the current status or developments in this plant were obtained.

Thermafuel system

A pyrolysis system for the conversion of post user plastics waste into a synthetic fuel exhibiting diesel fuel properties complying with EU fuel standard EN590, has been developed by the Australian company Ozmotech Pty Ltd. Modular pyrolysis systems with capacities of 10 and 20 tonnes of post consumer plastics per day (depending on the scale of plant constructed) are now commercially available. Construction of the plants takes place in a large production facility in Australia prior to being shipped, thereby economies of scale are achieved in production (Connelly, pers comm., 2005). Thermofuel plants with 20 tonne/day capacity cost in the region of £2.8 Million (€4.1 million) 'Free on Board' from Melbourne Australia (excluding insurance, freight, pre-treatment equipment, land acquisition (~750m^2) and fuel storage equipment which are extra costs) (Henry, pers comm., 2005). No plants are currently in place within Europe to obtain full installation costs.

Pre-treatment of the plastics feedstock is required in the form of size reduction to 12-15mm flakes and removal of heteroatom (e.g. chlorine, sulphur and nitrogen) containing plastics including PET, PUR, and PVC (including products containing PVDC barrier resins) and flame-retardant additives (accepted up to 3% by weight of feedstock). Preferred feedstock wastes include PE, PP and PS which are the most suitable for producing high fuel yields, with ABS, PA and EVA being accepted in mixed polymer streams. Float-sink density separation is considered adequate to separate out the desirable and undesirable fractions. Contamination levels (not exceeding 10% by weight) of paper, food residues, aluminium in multilayer packaging etc can be tolerated and remain as char. From one tonne of mixed polyolefin waste entering the plant, a typical output mass balance is 82% hydrocarbon distillate, 4% char, 4% losses in the desulphurisation process, 4% losses of non-condensable gases (returned to the system as process fuel) and 6% olefin residual liquid (which has degreasing properties and a marketable value) (Ozmotech, 2005).

There are currently twelve such units proposed to be installed throughout Europe over the coming seven years the first of which is anticipated to start operating in Ireland in June 2006. Contracts have been obtained with farm plastic collection firms in Ireland for PE film too contaminated to mechanically recycle and other contracts with collection companies are currently in discussion (Connelly, pers comm., 2005). Planning permission for seven 20 tonne/day units in the UK and Ireland, with a further five in Spain is being sought with each plant having typical potential yield of 16 500 litres of diesel per day provided sufficient quantities of post use plastics can be acquired. In total thirty two Thermafuel modular pyrolysis plants are anticipated to be installed throughout Europe by 2012 in Spain, the UK, Ireland, France and Germany (Henry, pers comm., 2005).

Production costs (excluding collection and pre-treatment) for diesel fuel in a 20 t/day system are reportedly in the region of £0.13 (€0.19)/litre. The market for diesel fuel is relatively abundant thereby securing a viable market outlet for the produce. It is anticipated that this favourable market for the product shall also allow for pre-sorted waste to be bought for up to £50 (€75)/tonne. A gate charge for heavily contaminated or mixed waste requiring separation shall be required although this is anticipated to be in the region of £40 (€60)/tonne (Connelly pers comm., 2005) which is comparable with incineration plants throughout Europe (however pre-treatment and obtaining waste supply is still to be tested and proven within Europe).

The Spanish government are exempting the resultant diesel fuel from fuel taxation on the basis that it is a recycled product and Germany and France are also reportedly looking into allowing the same concession to be made, however within the UK, due to the feedstock being non-renewable, regular diesel fuel tax shall apply. Other issues surrounding the wider implementation of such systems are, within the UK and Ireland, reportedly planning permission processes which have been suggested to affect the development of many waste treatment facilities (Connelly pers com, 2005). A 20 Tonne/day plant shall have the capacity to process approximately 7 000 tonnes of waste per year (giving time for maintenance etc) making this process relatively small scale in comparison to other recovery processes. Diesel production shall be some 5 – 6 million litres per year.

Project POLSCO, Polymer cracking

In 1994, BP Chemicals in a research and development consortium including APME, Autofina, DSM, Enichem and Petrofina began investigating the viability of feedstock polymer cracking. The research centred on developing a feedstock recycling process which could break down polymer wastes to the basic hydrocarbon feedstock.

As a result of the R&D work, a pilot plant with a capacity of 50kg of mixed plastics waste per hour was constructed at BP Chemical's Grangemouth oil refinery in Scotland. Between 1994 and 1999 trials were carried out using mixed plastics waste feed in a system based on a fluidised bed reactor. The developed process cracked plastics waste into hydrogen gases which were subsequently condensed into oil. The oil could then be processed within a petrochemical refinery to produce new monomers and subsequent polymers for the creation of new plastics (Beattie, pers comm., 2005).

The pilot plant was successful and demonstrated that this process could be developed and operated effectively. It was found that the mixed plastics cracked (broke down) into shorter hydrocarbons including PE and PP into paraffins, PS into styrene and aromatic compounds, PVC into hydrocarbons and hydrogen chloride, along with other similar products from other plastics. The benefit of the process is that mixed waste can be processed without the necessity for high level separation and only a limited amount of pre-treatment is required to reduce the size of the polymers. Contaminants that would otherwise be problematic in mechanical and chemical recycling such as fillers, food residues, and heavy metals would remain in the fluidised bed sand and could be retrieved later. Acidic gases could be cleansed through the use of scrubbers in the flue gas treatment (Hulse, 2000).

The process cracked plastics into a purified hydrocarbon oil with yields of more than 80% of the feed plastic hydrocarbon content with further steam cracking in a refinery producing ethylene and propylene yields similar to conventional fossil mineral feedstock. However, having established that the process was achievable BP chemicals decided that in order to take the process further, it would mean diversifying into waste management and away from their core business. Therefore in 1998 a new group was formed combining the technical knowledge of BP chemicals, Valpak Ltd (a UK Producer Responsibility Organisation), and the waste collection company Shanks Waste Solutions. The project had the aim to carry out a feasibility study to assess the potential for developing the technology into a full scale recycling plant utilising the MSW plastics obtainable from the central belt of Scotland. The project, which was completed in mid 2000, determined that a plant capable of processing 25,000 tonnes per year of mixed plastics waste could be developed and run from the available household plastics waste alone. However it was also identified that it would take four years and £25 million (~€ 37 million) to set up a full scale plant and a substantial gate fee of around £180 (~€270/tonne would be required to be charged for waste entering the plant to cover investment and operating costs. There would be the relatively small and variable income from the UK tradable Packaging Recovery Note (PRN) system and sale of product (in 1998 estimated to be £100 (~€145)/tonne of mixed plastic feed however would vary depending on virgin mineral oil prices) (Beattie, pers comm., 2005).

Although the project effectively demonstrated that the technology was indeed achievable in producing a stable hydrocarbon source as a product and could process mixed wastes without high separation and associated costs, the economics of a full scale plant were reportedly too great to justify any of the parties involved developing it further. The requirement to be located near to or have the ability (both physically and financially) to transport the resultant products to an oil refinery also limit its location. Therefore this has remained as a proven, but as yet not adopted technology for the plastics waste management industry (Beattie, pers comm., 2005).

6.2.2.2 Advanced PVC Recycling processes

Given the difficulties and challenges associated with PVC recycling (as detailed in appendix 5) and the voluntary commitment of the PVC industry to increase PVC recycling, a number of research and development projects are being investigated in order to enhance PVC recycling. Vinyl2010 report a number of developments and advances in the amount of mechanical PVC recycling being conducted throughout Europe with Window profiles, pipes and PVC roof and flooring materials being increasingly recycled. However Greenpeace widely dispute the figures published and state that the majority of PVC products reportedly produced from post consumer recycled products are largely obtained from production waste and not post consumer material (Greenpeace 1999 (and subsequent press releases)). PVC waste production is however set to increase due to the long life applications in which it is used. Waste arisings are not expected to mirror current production levels until at least 2020 when long life products enter the waste stream (see Plinke, Wenk, Wolff, Castiglione, Palmark, 2000 for in-depth report). However, trial projects for more effective recycling of PVC have been established.

Solvay Vinyloop PVC Mechanical recovery process

Developed by the major PVC manufacturer Solvay largely in response to growing pressure from a major customer, Ferrari Textiles Techniques (France), which produces architectural tarpaulin and canvas in PVC/ Polyester compounds (Solvay, 1999). The recycling of this material by conventional mechanical recycling was found to be unsuitable due to the polymer mix and therefore an alternative technique was required.

The Vinyloop concept for PVC employs a similar process to that of the Hybrid UnPET in that it combines the use of a chemical agent and mechanical recycling in order to achieve the desired quality of recyclate. However where as the chemical agent within the Hybrid UnPET dissolves fractions of waste other than PET, in the Vinyloop process, the chemical agent selectively dissolves the PVC. Other elements such as rubber, polyethylene and metals remain and can be filtered and extracted from the system. The PVC can then be precipitated out off the solution with the solvent returning to the process and the PVC (including original additives) remains as fine granulate. Due to the different colours of the original waste feedstock carbon black is added to give a uniform black compound.

A 10,000 tonnes/year capacity demonstration facility was constructed in Ferrara, Italy in 2002. However problems have been encountered in the quality of waste accepted and the pre-treatment stage. Full commercialisation and operations have thus not been achieved as yet and, although no precise details were obtained it is believed that relatively high gate charges of between €200-300/tonne are set in order to recuperate investment costs. This has lead to low volumes of waste being delivered to the plant for reprocessing (Vinyloop, 2005; Ludvigsen pers comm., 2005). In order to facilitate its access to waste products the Vinyloop plant at Ferrara operates in partnership with local producers including SolVin (Solvay/BASF JV), Adriaplast (Solvay's industrial foils subsidiary), Tecnometal, an Italian electric cables recycler, and Vulcaflex, which produces calendared foils and artificial leather.

RGS90 PVC Chemical recycling Denmark

In 1998 development and construction began on a chemical recycling plant for PVC by the company Stigsnæs Industrimiljo AS under the parent company of RGS90 at Skælskør, Denmark. Building on previous research and development in the field of PVC cable waste which was conducted from 1993 a full scale plant was successfully constructed in 2004. A testing phase is now being conducted which has been ongoing since the end of 2004.

The plant itself is based on a two stage process the first of which involves de-chlorination by mixing the pre-granulated PVC with sodium hydroxide with the resultant fluid mix being pumped through a hydrolysis pipe reactor at a temperature of around 260°C producing sodium chloride and a solid fraction. The sodium chloride solution can then be filtered through a membrane to allow a purified NaCl solution which is distilled to extract industrial grade NaCl salt. The solid fraction from the pipe hydrolysis reactor along with the substances that were not passed through the membrane with the salt (which includes heavy metals and phthalates) then enters the second stage of the plant. This second stage involves a low temperature pyrolysis process in which the solid phase thermally decomposes into a liquid hydrocarbon rich oil fraction with a coke solid fraction. The phthalates from the PVC are condensed out into the oil and heavy metals are retained within the coke fraction (Ludvigsen pers comm., 2005).

Early indications were that the full scale plant would be operational and capable of accepting 50 - 100 thousand tonnes/year of post use PVC by the summer of 2005. However the system has been plagued by a series of technical and operational problems and to date has only tested 1200 tonnes of waste since trials began in 2004 (Ludvigsen pers comm., 2005).

Prior to the PVC waste entering the plant a pre-treatment process must first be undertaken in-order to remove large major contaminants. The original shredder unit and granulation pre-treatment system utilized was unable to remove mixed metals, fibres and stones present in the material delivered. This has resulted in modifications and a cleaner material feed fraction being required. As of August 2005 six test runs had been carried out on this process, each time resulting in a blockage occurring after 2 days of operation. This problem lies in two areas: the first of which is that the light PVC film fractions melt to the pipe reactor wall and accumulates build up material around it; the second problematic area is the presence of heavy PVC fractions and contaminants of copper wire which fall to the bottom of the tubes, again causing obstructions and resulting in the flow being restricted. Due to this the pyrolysis process has not yet been fully tested as the resulting feed supply for this has not been obtained as yet (Ludvigsen, pers comm. 2005).

Other issues affecting the viability of the RGS90 plant relate to the availability and sourcing of PVC feed for the system one of which is largely due, although not limited to, the aforementioned problems which have resulted in the need for sourcing a cleaner waste fraction than originally anticipated. PVC, as with any other plastics waste, is traded on free market conditions and as the clean fraction of PVC waste can generally command a price and thereby be sold by collection companies or taken for little to no money by recyclers in Europe or abroad rather than pay for recycling the material (in 2004, 25% of the PVC waste arising in Denmark was exported the Far East for recycling). The relatively low price for landfilling and incineration also affects sourcing material domestically and from other EU member states. This has particularly affected the process as the gate fee required to be charged for incoming material is currently €200 (£135)/tonne in order to cover development and operating costs (Ludvigsen, pers comm. 2005). The proposal for EU wide legislation stemming from the PVC Green Paper not coming into force has also affected the business case on which the plant was based. In October 2005 the plant was put on hold due to financial deficit and the difficulties in lowering the gate fee to a price which would attract further feed material deliveries and therefore is not anticipated to operate on a commercial scale at present (Børsen, 2005).

6.2.2.3 Advanced energy recovery

A number of pyrolysis, gasification and autoclave facilities for the treatment of MSW and RDF (including among the feedstock, plastics waste) have begun commercial operation throughout Europe processing similar waste streams to mass burn incineration plants. With the increasing use of MBT facilities the use of such technologies is set to increase. Due to the scope of this work these are not described within this report. However two plants that recover energy directly from plastics waste specifically are briefly introduced forthwith (these are presented separately from feedstock or chemical recycling plants due to the process recovering energy exclusively with no spatial or temporal separation from production to utilisation or other by product utilisation).

Poligas Gasification plant, Spain

A gasification plant for contaminated plastics packaging from the ceramic industry, other plastics waste and residues from the olive oil processing industry, developed by 'Enerkem Technologies', was constructed in Ribesalbes, near Castellón, Spain and began operating in 2001 by 'Poligas Ambiente S.L.'. The plant allegedly has a nominal capacity to process 20,000 tons per year utilising the gas to produce electricity through an installed 7.3 MW gas turbine (Williams, Jenkins & Nguyen, 2003) Equipment investment costs are believed to be in the region of £7.7 Million (€11.5 Million) (Enviro-Accès, 2003). Local opposition to the plant due to concerns surrounding the risk of toxic gases being released from ceramic industry waste with the plant operating on extended leave of test until now have been reported in local media (Priorat, 2005). However no confirmation regarding this and limited further information for this plant has been obtainable from the company and the current status, operating and gate fee costs are unknown.

ECOGAS Energy Plant, Varkaus, Finland

A bubbling fluidised bed gasification plant developed by Foster Wheeler operates at Corenso United Oy Ltd (a major paper and multi-material-layer packaging manufacturer) in Finland. Post-consumer multilayer packaging material (including cardboard, PE film and aluminium foil layers e.g. Tetrapak cartons) collected within Finland is recycled by separating as much of the cellulose material (which is utilized in the production of paper) from the plastic and aluminium as possible which is then processed in the gasification plant. Around 29 000 tonnes of polyethylene per year is gasified with energy being recovered through a 40 MW gas turbine which provides electricity for the manufacturing facility with excess sold to the national grid. Around 3 000 tonnes per year of aluminium is recovered from the gas stream and sold to a German aluminium re-processor, the combination of activities allows the company to fulfil their recycling and recovery obligation while beneficially utilising their reclaimed products and obtaining a guaranteed feedstock for the process (Williams *et al.*, 2003; Corenso, 2005). Limited information regarding the operational issues and economics of this plant was obtained.

Recovery in Cement Kilns

Cement production requires a large amount of fuel to achieve the >1200°C required in the production kiln to form clinker. Conventional fuels such as oil, coal or gas can be supplemented by high calorific waste materials (co-incineration) such as plastics as an energy recovery option (the destruction of hazardous and low calorific waste by the high temperature is also practised which is seen as disposal). Although this is regarded as energy recovery for pure polymer resins, where composite materials are utilized this may be viewed as a recycling method as the inorganic fraction substitutes conventional clinker production materials such as lime, clay gypsum etc while the organic fraction contributes to the energy input of the production process (Sander, *et al.*, 2004). Therefore this is regarded by some as feedstock, or in certain instances where the inorganic fraction of the material is high, material recycling (Sander *et al.*, 2004; Tukker *et al.*, 1999). However, boron present in glass fibres can have the effect of increasing the time cement takes to dry and quantities of >0.2% boron in the cement can cause this effect, therefore no more than 10% of the fuel input to the cement production can be composite material (Pickering, 2005). Calcium carbonate fillers can on the other hand be beneficial and act in a similar way as powdered limestone that is commonly utilized to remove oxides of sulphur from the flue gas. In terms if statistical data gathering this is relatively hard to quantify what percentage is entering the clinker and that which is combusted, the process is therefore generally seen as an energy recovery operation.

In terms of capacity for treating waste plastics in this way, Tukker *et al.,* (1999) estimated that approximately 3 million tonnes of potential capacity exists within Western Europe. Given that cement kilns, as with the Blast Furnace process, are constructed for a purpose other than waste disposal, therefore gate fees are not required to cover capital investment in construction costs. As a result of this only pre-treatment and in-feed system costs are required to be covered, the gate fee has been estimated to range from 0 – 100 Euros per tonne of waste. At present some 200 thousand tonnes of plastics waste is utilized in cement kilns throughout Europe with more cement manufacturers looking favourably at refuse derived fuel as an alternative to traditional fuel sources (letsrecycle, 2004)

6.2.2.4 Related issues affecting advanced recovery options

In achieving the establishment and development of new technologies and innovative processes to treat post use plastics there are substantial issues to overcome. Innovation systems which have been defined as "*the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge*" are regarded as a key drivers to new technology entering commercial use to benefit society as a whole (Foxon, Gross, Chase, Howes, Arnall & Anderson, 2005). Within innovation systems several failures and gaps can occur in the development process from pilot projects to full scale industrial commercialisation. These have been determined by Foxon *et al.,* (2005) (in reference to renewable energy technologies however these same issues have been identified in plastics recovery technology development), to include:

- *Technology risks*: relating to whether the process will achieve expected performance levels, efficiency improvements and cost reductions when scaled up from pilot to full scale industrial processes.

- *Market risk*: The uncertainty of future levels of return for product produced.

- *Regulatory risk*: where markets are created by policy mechanisms associated risks are taken due to the fact that social institution priorities or governing parties may change.

- *Systems risk*: associated with disruptive technologies which maybe perceived as inherently complex by stakeholder and which require changes to existing technologies and/or institutional systems (e.g. Combined Heat and Power plants).

6.2.3 Incineration (Energy from waste)

Incineration and co-combustion capacity has grown and continues to grow throughout Europe in recent years. This sector has developed substantially in terms of technological advances in emission abatement, energy recovery efficiency as well as recovery of inorganic and chemical components within the waste feed in the past 10-15 years. This has largely been due to legislative requirements such as the Waste incineration Directive, the IPPC Directive as well as other environmental policies such as the OSPAR convention. Further developments are ongoing with techniques that limit costs, improve environmental performance and recover more value from the wastes (EIPPC, 2005b).

There has been some legal uncertainty surrounding the classification of waste specific incineration plants being classed as a recovery option. The European Court of Justice ruled that burning waste in energy from waste plants does not count as energy recovery because the plant is designed specifically to dispose of waste. In contrast the court ruled that cement kilns and blast furnaces are recovery due to the fact that they exist to make cement or Iron rather than disposing of waste. However the recent proposed amendments to the Waste Framework Directive indicate that this shall change stating that "operations that result in the waste serving a useful purpose in replacing other resources, whether in the plant or in the wider economy, which would have been used to fulfil that function, or prepare waste for such a use" (Cartledge, 2005). Although legal uncertainty has surrounded the classification a number of EU countries, having introduced bans on the landfilling of combustible waste are seeing marked increases in the volumes of mixed (including plastics) waste going to incineration and more facilities have been proposed in National Waste Strategy documents.

Within Germany new legislation forbidding the landfill of untreated waste and imposing a requirement that all residual waste (i.e. not source separated) is treated in Mechanical Biological Treatment (MBT) facilities and that the resultant Refuse Derived Fuel (RDF) is treated through energy recovery incineration has lead to a substantial rise in waste incineration. This came in to effect on the 1st of June 2005. In the run up to the implementation date landfill operators were reportedly dropping their gate fees to an absolute minimum (~€35/tonne[††††]) in order to take advantage of the last large deliveries of waste to their sites and fill open void space in a number of sites prior to closing. This lead to energy recovery incineration facilities operating under capacity due to higher gate fees (~€150/tonne) having to be charged than the landfill operators were. Since June the situation has changed and incineration capacity has been exceeded with gate charges rising (€150 - €350/tonne) due to energy recovery demand being high. It is anticipated that this will change in the future as more sorting capacities for plastics and other wastes being established in light of the situation and new recovery/incineration capacity being established as well (Quoden, pers comm., 2005). Germany has also recently classified RDF from MBT processes as 'non-waste' and therefore plastics remaining in waste after that which has been reclaimed for recycling shall enter the RDF fraction enabling combustion in power stations which do not meet the emission control standards of the waste incineration directive or be confined to Transfrontier shipment of waste requirements. Within the revisions to the Waste Framework Directive currently being proposed the EU may use environmental and fitness for use criteria to determine when waste ceases to be waste which may include the RDF classification already introduced by Germany (ENDS, 2005f).

As mentioned previously in section 4.2.3, the thermal recovery ratio of MSW incinerators varies between plants and has been determined to range from 11% to 73% in German incineration plants as an example. Within Norway the incineration of plastics waste does not count towards recovery unless 50% of the heat energy of the waste is recovered thereby promoting the use of more efficient incineration plants or alternative (i.e. feedstock recycling) facilities (Schefte, pers comm., 2005).

Developments in recovering chlorine from PVC co-combusted with MSW have entered into use with six of the fifty nine incineration plants in operation within Germany having the capability to recover chlorine as Hydrochloric acid in industrial quality and utilize acid scrubbers to wash out the halogen compounds HCl, HF, HBr and HI. However within this process reportedly only 50% of chlorine is recovered where as in the vinyloop and RGS90 processes chlorine recovery is as high as 94% to 99% (Kreißig, Baitz, Schmid, Kleine-Möllhoff, & Mersiowsky, 2003). Concerns about the potential environmental and health impacts of some flame retardants found in WEEE plastics have given rise to suggestions that energy recovery is the most environmentally efficient option to treat components containing brominated flame retardants. The argument is made that the focus should be on sustainable

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[††††] although some sites remained as high as €200/tonne where no incineration facilities are within the vicinity.

energy recovery with the ability to capture substances of concern rather than mechanical recycling as the alternative to landfilling. Modern MSW Incinerators complying to the Incineration and IPPC Directives, with extensive air cleaning and residual ash management capabilities, are potentially valuable energy recovery options for mixed plastics from WEEE and ELVs. This particularly concerns those containing flame retardants, due to the ability of some thermal conversion facilites to destroy certain halogenated organic compounds.

Other processes have been developed and are entering into use including techniques for recovering high grade inorganic fillers such as glass or carbon fibre from composites combusted within fluidised bed processes. The fibre can subsequently be utilized in new composite production (Pickering, 2005).

Although incineration with energy recovery is regarded by several stakeholders as a viable, resource utilisation justifiable, alternative to landfill for residue wastes that are not recyclable, it is widely argued against by a number of organisations and the general public. Core arguments include the impact of dioxin, furan and other detrimental emissions as well as that due to incineration requiring a constant supply of waste it removes the emphasis from promoting recycling. This is particularly pertinent in certain EU countries, especially within the UK, Ireland, Spain, Portugal, Italy and Greece. Public opposition to new incineration plants is strong within the UK (which currently has 14 operating MSW incineration plants with a joint capacity of 2million tonnes/year (compared to France with similar population and density has 123 operational plants with 16million tonne/ per year capacity) (EIPPC, 2005b)). A number of plants proposed within the UK National Waste Strategy documents are not to be constructed due to local objection. Of the six plants proposed to be constructed in 1999 those in Aberdeen, Nottingham and London have been refused planning permission largely due to NIMBY objection (Maitland, pers comm., 2005). High development costs are also a major issue associated with waste incineration costs with EfW plant reportedly often requiring a capital investment of over £50 Million (€73 Million) (Eyre, 1999).

However, countries that have had historically utilized incineration as the dominant MSW and other waste stream management option for example Switzerland and to lesser extent Denmark, Sweden and the Netherlands have improved recycling rates even with incineration being utilized to a larger extent than countries such as the UK and Ireland. Switzerland has increased plastics recycling despite traditionally relying upon incineration due to limited void space for landfill. Price mechanisms are the main instrument employed to ensure incineration does not remove materials from the material cycle. Switzerland, which had in the past subsidised incineration have now discontinued subsidisation and charge households for waste volumes not source separated for recycling (Green Alliance, 2002). Denmark and Norway and Flanders have introduced waste incineration taxes and Sweden are currently proposing and discussing introducing an incineration tax from 2006 (Idefjell, pers comm., 2005).

6.2.4 Bioplastic developments

Recently bioplastics have been attracting increasing amounts of attention from many sectors and entering onto the market in ever increasing quantities. Examples of new and increasing use include applications such as beverage bottles that are beginning to be produced from PLA as a replacement for PET for non-carbonated drinks packaging in Europe by the packaging manufacturer Amcor. As PET prices have risen in recent months and years, and production costs of PLA and other RRM based resins has fallen as production capacity and processing techniques have improved, RRM polymers are becoming a more competitive and attractive option for packaging applications. Nestle UK have also recently announced that Plantic starch based bioplastics are to be used for their 'Dairy Box' chocolate packaging. An increasing amount of other producers are also considering the use of bio-plastics as an option for their packaging materials in response to rising petrochemical based polymers. The falling price of RRM based polymers and the responsibility placed upon producers to recover and recycle their packaging waste are all driving further developments (Shnarr, pers comm., 2005; Omnexus, 2005). Automotive industries are also researching their use in vehicle applications with Toyota establishing a pilot PLA production plant in Japan in August 2004 with plans to develop a full scale plant in the near future. Toyota already utilize PLA in automotive parts to replace PVC (ENDS, 2004a).

Figure 21: Identification symbol for biodegradable plastics (IBAW, 2005 reproduced by permission of Mr. M. Shnarr)

As treatment, collection and sorting infrastructure for the composting, biomethanization and thermal processing of biodegradable waste grows in response to the landfill directive's stipulations for the diversion of such waste from landfill sites the capacity and capability for treating biodegradable and bio-polymers has increased. The international industry platform for bio-plastics and biodegradable polymers (IBAW) has introduced an identification symbol for biodegradable plastics to aid the separation and inform consumers that the material shall degrade through hydrolysis shown in figure 21. The criteria for accrediting polymers in this way is based on the German standard test method DIN V54900 in order to ensure the products do compost within a given time and to a predetermined quality.

A trial to promote and increase the use of biodegradable packing and to analyse the effect of recycling options available for such products via the municipal organic waste collection system was conducted from May 2001 to November 2002 in the German city of Kassel. In total 31 tonnes of RRM based biodegradable and compostable packaging materials were introduced into the market through local retailers in a number of products all clearly marked with the compostable symbol. Collection was carried out by use of the existing DSD bio-waste bins system and further sorted for contaminants at a manual MRF with the resultant product examined and tested in a commercial composting facility. The safe use of the compost produced from these materials was demonstrated by regular compost analysis and in a full-scale agricultural application test. The collection infrastructure was deemed to be successful in collecting the materials with a 65% collection rate with no apparent increase in the amount of impurities in the bio-bin being detected. The processing of BDP in composting facilities is possible though it was determined that some additional manual separation was required at MRFs and when volumes were high separation of bio-polymers from conventional polymer plastic materials was more difficult. The use of the compost for agricultural purposes was determined to have no negative effects on plant yields and soil contamination levels (Klauss & Bidlingmaier, 2003). The results do not however present any information regarding the occurrence or impact of bio-plastics entering the conventional petrochemical based plastics recycling system.

The combustion of bio-plastics in MSW Incinerators for energy recovery can also be classed as a renewable energy resource although the total calorific value of different bio-plastics has not been determined within this research. As bio-energy plants enter into wider spread use throughout Europe Bio-plastics may also offer a suitable alternative feed stock for these plants although the volumes utilized and separately collected have not been high enough as yet to justify trials of this type within Europe. This is regarded likely to be a viable mid to long term option for bioplastics (Schnarr, pers comm., 2005).

7. Discussion on implications of developments

Within this chapter the identified developments and issues raised in chapter 6 are reflected upon in relation to those presented within chapters 2 to 5. The implications of the issues raised throughout this research are brought into the combined context of the waste hierarchy and integrated waste management in order to identify how the management of plastic resources can transition up the waste hierarchy and what the major barriers are to achieving this.

The concepts of the waste management hierarchy and integrated waste management have previously been introduced. The waste hierarchy can be seen to act as an aid in defining the direction for which an integrated management system should prioritise. An integrated waste system has been identified to be preferable, as, what is "best" for one region and waste stream differs substantially due to social, political, geographical, economic and other variances. Figure 22 combines both these concepts, with integrated waste management in the centre and the waste hierarchy acting as the surrounding guiding principle. This largely illustrates the general vision and goal of the European Union in developing an optimal waste management system by making use of the most environmentally favourable treatment options available.

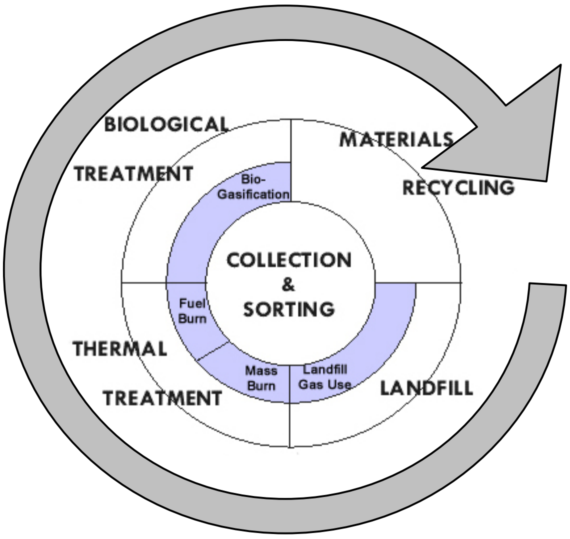

Figure 22: The concept of integrated waste management in conjunction with the waste hierarchy (adapted from IWM and LCA, 2004)

Although the current situation in Western Europe as a whole is that landfill remains the dominant option for end-of-life plastics, political and social intervention as well as other factors, are having an affect on their dominance. Substantial movements have been made in certain countries to dramatically limit their use. The stipulations of the EU Landfill Directive have resulted in a number of non-compliant sites to close. These have also increased the price associated with remaining sites due to the technical construction requirements imposed increasing operational costs. Landfill taxes introduced in a number of individual member states are also internalising the external costs associated with landfill and making alternative treatment processes such as recycling financially more attractive. The funds from such taxes are also aiding the research, development and establishment of alternative treatment options. Landfill bans on organic, untreated waste or MSW, as introduced in such countries as Sweden and Germany for example, are making alternative options such as energy recovery, composting and recycling the only option for certain wastes, although due to collection and capacity issues with alternatives, this situation has not been achieved quite yet.

Non-policy factors are also making alternatives more attractive as capacity in existing sites reduces and new sites are increasingly difficult to establish due to less available land, increasing land costs and local objection to new sites. This is however regionally specific and in certain areas landfill remains dominant and void space is not a major limiting factor. Landfill does have an important role in an integrated waste management system at present including for the disposal of ashes from thermal treatment facilities. The major problems associated with plastics are their high volume which, due to the fact that they do not readily decompose, substantially reduces the operating life of sites. The fact that it is seen as a waste of resources is also a further issue. It has been ascertained that certain plastics that contain additives, which can be leached out of the materials, entering the gas emissions and liquid effluent, are detrimental to the environment. The full extent of the affect plastics (petrochemical and RRM based) have in landfill sites is largely unknown due to their existence within society being only around 50 years and landfill investigations have found that polymers can remain intact within sites for this time. Therefore a precautionary approach is taken, and utilisation of the resources, whether for material or energy recovery, has benefits to both the economy and environment in many instances. If the latest proposal by the European Parliament for more stringent landfill bans come into force then it is proposed that there shall be an 80% ban on plastics and other recoverable wastes going to landfill by 2015 increasing to 90% by 2020 (ECOLA-PIRA, 2005). Given the present situation this would appear to be difficult for several member states to implement within this time period highlighting the requirement for the development and investment in alternatives in order to move away from disposal.

Although available, alternatives to landfill do have a number of inherent limiting factors. The drivers, barriers and developments identified within previous chapters shall be reviewed. Their implications on further achieving a move away from disposal and transitioning up the waste management hierarchy in a system that optimises the use of available technologies shall be discussed in the following subchapters.

7.1 Bio-polymers

Bio-polymers are penetrating into the petrochemical polymer dominated market in increasing quantities and applications, and do offer significant energy savings over the use of petrochemical based polymers (see appendix 4). Production capacity developments enabling economies of scale and associated price reductions along with increasing prices and attention being paid to finite fossil mineral resource are making bio-polymers competitive with conventional polymers and increasingly attractive to various sectors. Packaging and agricultural films are the main target sectors for bio-polymer producers at present. Mulch films are utilized widely within agriculture across Europe. The fact that they are relatively short lived, lasting up to 6 months at the end of which, being contaminated with soil, fertilizers and moisture and tend to have degraded through UV light, often inhibits their ability to be recycled. Remote geographical locations in which they are utilized also affect the effectiveness and efficiency in which they can be collected. Therefore bio-polymers offer a viable alternative. At the end of life compostable mulch films can be ploughed into the field and the potential exists to impregnate them with fertilizers or other beneficial substances such as lime to aid crop production. The use of biodegradables may also reduce the aesthetic degradation of the country side which is often caused by agricultural film being blown into tress and fences and potentially affecting animal welfare due to ingestion. It has also been seen that a substantial volume of agricultural plastics are combusted on farm by open burning in certain locations leading to significant emissions of dioxins and PAHs into the atmosphere. Therefore

RRM based degradable polymers do offer a number of advantages to agriculture and in reducing the environmental burden of such activities.

Within food packaging bio-polymers also have advantages over and above those of reducing reliance upon fossil mineral resources. Food packaging stipulations require that diffusion and migration of substances of concern does not take place between the packaging material and the food product. The wide, and increasing, variety of polymers and potential contaminants within these materials also affects recycling. These have been stated to be the main inhibitors to closed loop recycling of food packaging materials which contributed ~7 million tonnes to waste arisings in 2002 (representing 33% of total plastics waste). The efficient collection of plastics from the MSW stream is also affected by wide geographical distribution, especially in low population density regions. With MBT facilities being established in a number of countries (particularly Germany and the UK) and as composting infrastructure develops to meet the stipulations of the landfill directive, providing alternative treatments for compostable bio-polymers this may encourage the wider adoption of such alternative polymer packaging. Where MSW incineration is the predominant waste treatment option employed, RRM based polymers also offer a viable renewable energy fuel source, without detrimental additive aspects affecting emissions (such as the case with PVC). The properties of bio-polymers (see appendix 4) also make packaging a viable product for which to utilize these material. Given the short life span of food packaging premature degradation is also a reduced factor to consider.

As bio-polymer applications such as PLA packaging trays and bottles, which have very similar properties and visual characteristics to PET, an effective and efficient separation system is required to be adopted so as to ensure these two polymer types do not become commingled in the recycling process (small amounts of PLA causes clouding and degradation of PET recyclate). Trials in Germany have shown that source separation can aid this, however inevitably some volumes of PLA shall enter the PET system if the current trend in development and adoption of PLA continues. Bio-polymers do have advantages over petrochemical polymers and the infrastructure needs to be in place in order that their further market penetration is not impeded by recycling targets and systems set for conventional plastic products. Therefore automated separation of mixed polymer waste streams is a viable and effective means of separation and the case for their wider utilisation is justified in order to ensure biopolymers do not inhibit conventional polymer recycling routes.

Given that the technology does exist to produce, and markets are available for bio-polymers, the fact that only 0.001% of Western Europe's plastic production and consumption consisted of bio-polymers in 2004 illustrates the dominance of petrochemical polymers. Estimates indicate that the percentage of bio-polymer plastics shall rise to 2% of global plastic production and consumption by 2020. Therefore bio-plastics are not likely to constitute a major proportion of plastic production and consumption for some time, highlighting the requirement to manage current conventional plastics as efficiently as possible. Global fossil mineral resource prices have been increasing substantially in recent years and months for a reason, demand is exceeding supply. Although this trend may not continue, as the market, through price mechanisms, regulates scarcity along with extraction and supply increasing to compensate, the recent situation has highlighted the fact that the price volatility of petrochemical resources can cause acute economic impacts. Therefore bio-polymers do offer a viable and necessary alternative to dependence on such resources and offer benefits to the entire life cycle of a number of products and can aid more sustainable production and consumption along with potentially stabilising the market price by securing supply of feedstock materials.

Summary

RRM based Bio-polymers are entering into the market in increasing volumes. The dominance and established markets of petrochemical based polymers do cause some issues in the further acceptance of bio-polymer development however:

- Although the cost associated with bio-polymers is reducing, petrochemical based plastics remain an often cheaper and more established material making the penetration of RRM based plastics into the market difficult in some applications. Capacity in production of bio-polymers remains low within Western Europe;
- Similar characteristics of certain bio-polymers and conventional plastics along with incompatibility in mechanical recycling make separation more complex and may inhibit market growth;

Drivers and opportunities

- Production capacity is increasing and economies of scale are bringing costs down. Concurrently, increasing petrochemical prices are reducing the cost disparities between the polymer types;
- RRM based polymer prices are relatively stable in comparison with petrochemical based polymers reducing volatile nature of the market which affects processors costs.
- Increasing social acceptance and attitudes favouring renewable resource are encouraging manufacturers to utilize RRM based plastics;
- Additives such as heavy metals, phthalates and other substances of concern are not generally utilized or required in these materials;
- Developing composting and bio-energy production facilities offer viable, sustainable and increasingly available treatment options.

7.2 Mechanical recycling

Mechanical recycling is the most developed and widely utilized material recycling technique utilized in the plastics waste management industry. The benefits in energy, emissions and natural resource savings associated with recycling homogenous post use thermoplastics, provided that collection operations do not exceed savings made, have been determined to prevail over other treatment options for a select number of polymers and product types. Therefore mechanical recycling plays an important role in an integrated waste management system as the preferable route for a number of plastic wastes arising.

Issues affecting the mechanical recycling of plastics from various products and waste streams are numerous and emanate from several factors. There is substantial capacity available within Western Europe for recycling of the large volume thermoplastics of PE, PET and PP. Based on interview results with recycling companies, utilisation of available capacity would appear to be approximately 60%. This illustrates that capacity does exist to increase recycling rates if homogenous resins can be obtained, which there is a lack off at present. Viable market outlets for these materials are established and demand is increasing. This is particularly pertinent in agricultural film and industrial distribution packaging applications where supply of post use materials, recycling capacity and demand for recyclate are all generally increasing. However these sources of plastics waste do require good source separation. The volumes and type of post use products from these sectors (mainly film and large pallets, drums and other containers) make them difficult or costly to centrally identify specific polymer types and separate into homogenous resins. Automated separation systems in commercial use and available do not generally have the ability to accept large objects or films. Therefore to reduce the financial costs associated with collection and recycling of these materials, proper information and guidance relating to source separation is a requirement in order to aid the further establishment of recycling in these sectors. Large potential does exist to further develop collection and recycling of these materials, which is not being realized in a number of regions due to a lack of initiative and information. Contamination does remain an issue, particularly in chemical packaging and agricultural mulch films. Although washing and cleaning techniques are available for these waste streams, advanced recovery or EfW incineration options provide a viable option from financial, practical and environmental aspects. Although outside the scope of this work, reusable containers are also in use however these inevitably enter the waste system at some point also. Bio-polymers as discussed can also provide a viable alternative in certain applications at present.

Technological innovation aspects

Innovation, the introduction into the economy of new knowledge or new combinations of old knowledge, is a key component in furthering the recycling and recovery of plastics waste. This is clearly important at all stages in the life cycle of products from design to waste management systems. A number of important innovative advances have been identified throughout this work which have enabled the establishment of new markets for recyclate and increased recycling rates.

Developments in re-processing techniques are aiding the development of certain markets and making recycling easier and more cost effective. These include developments in compatibilizers which are allowing higher grade materials to be produced from mixed polymer waste. However applications for such materials are largely limited to low end products such as sound barriers and signs along roads, other street furnishings and synthetic wood products which have limited markets. This "down-cycling" is also likely to have less environmental and financial benefit in the long term. Therefore development and establishment of high end markets for post use plastics and recyclate which has previously been identified to be one of the most important drivers to achieving an optimal recycling rate is essential to further promoting recycling. It has also been stated that demand for recycled plastics will increase when there is a reliable supply of appropriate quality materials and therefore is critical in establishing markets further.

New techniques being applied in the recycling of PET foodstuff packaging have facilitated closed loop recycling of food contact grade bottles thereby achieving high end markets. The URRC Hybrid UnPET, Erema and other technologies have overcome barriers associated with contaminant and diffusion of substances previously inhibiting the use of recycled plastics in foodstuff packaging. Further developments in this field are likely in the future with closed loop recycling of HDPE foodstuff packaging being researched and developed at present. Colour issues do still present a barrier to further closed loop recycling of packaging. Jazz PET and other coloured polymers remain difficult to market due to deep and mixed colour recyclate being of poor aesthetic quality and therefore inhibit their close loop mechanically recycling due to quality aspects, consumer and industry/designer preferences.

For these processes to be economically viable and attractive options for which to invest in, there requires being a secure and guaranteed source and mass of homogenous post consumer PET. Another constraint is that these mechanical recycling processes are required to process PET that has previously only been utilized in food contact applications. Therefore PET from other packaging applications such as cosmetic products is required to be identified and removed from such processes. The deposit refund and PET specific collection schemes such as those operating in Germany, Switzerland, Austria and Sweden where the majority of bottle-to-bottle recycling is taking place are aiding the development of these processes. These ensure the supply of high quality post consumer beverage bottle PET. Bottles collected through these EPR systems require limited further sorting as their previous use and polymer type is largely guaranteed. Therefore contamination is low and the requirement for further investment in high technology separation is reduced. With financial responsibility for collection being covered by producers' the cost and infrastructure development burden is removed from the general tax payer and recycling companies. The financial costs and risk involved in securing and obtaining feed materials is substantially reduced and not reliant upon local authority budgets and funding allocations.

The return on investment in such technologies is thereby largely influenced by the price obtainable for the recyclate. As higher quality markets are obtainable for the resultant regranulates, due to the quality assurance of the process, the market opportunities increase along with the revenue obtainable from the sale of recyclate. Lower processing costs are associated with the use of food contact approved recycled PET as multilayer performs (sandwiching recycled polymer between virgin layers) are no longer required and direct blow-moulding techniques with lower costs to processors can be performed.

The price obtainable for the recycled polymer is still dependent upon fluctuations in virgin polymer prices. With high virgin resin prices at present packaging manufacturers are being increasingly constrained by virgin polymer producers and large retailers. PET bottle processors therefore appear to see this as a viable and more secure source of material thereby increasing the market opportunities for PET recyclate. There is a significant risk that virgin polymer prices shall fall however, and if producers are to take more responsibility then minimum recycled content commitments may play an important role in ensuring demand continues. This may also encourage further investment and establishment in such processes throughout Europe as the 'market risk' associated with investing in such technologies shall reduce. The benefit in such a commitment is in establishing longer term contracts with the recycling industry and the risks are shared between recyclers and product manufacturers. This would result in a situation whereby if virgin polymer prices are high the manufacturers stand to gain in reduced material costs. If virgin polymer prices are low the recyclers stand to gain, over time this may likely benefit both parties as costs fluctuate.

PVC recycling is also being aided by 'advanced' mechanical recycling techniques. The Solvay Vinyloop process does offer the potential for more complex materials containing PVC to be recovered and recycled. However issues of cost, obtaining feed materials, and pre-treatment have affected the viability of this process. A further issue which affects PVC recycling and requires to be addressed are the additives utilized. Industry commitments and regulatory requirements are stipulating the substitution of substances of concern (e.g. certain phthalate plasticisers, heavy metal stabilizers etc) with less harmful substances. As these are replaced by less problematic substances in plastics produced today and in the future an evaluation of whether PVC, which contain substances of concern and remain in recyclate produced through conventional mechanical and advanced mechanical (i.e. the solvay vinyloop) recycling, is beneficial in the long term needs to be made. By removing these materials and the substances contained within them from the material cycle through chemical or feedstock recycling or EfW incineration, which can have the means to capture and remove them, new and less detrimental materials shall enter the system which is potentially beneficial for future recycling activities.

It has been identified that the capacity to recycle a number of polymer waste types arising is available. Various collection schemes and initiatives are developing rapidly in order to reclaim the materials from the waste streams. Advances in automated separation technologies are a major factor enabling higher volumes of homogenous polymers to be reclaimed from mixed polymer collection schemes as well as complex products such as ELVs and WEEE. It has been stated that as volumes of material entering MRFs from mixed municipal plastic collection systems increases, the ability for conventionally utilized manual separation to achieve high quality homogenous materials is substantially reduced. The costs associated with manual separation in Western Europe are also rising as labour costs increase. This is especially pertinent where more than one material is collected for recycling, for instance mixed plastic, metal, and beverage carton collection systems. It has also been previously illustrated that a number of advances have taken place in the automated polymer identification and separation technology sector in recent years. Several facilities have made investment and are benefiting from increased separation rates as the financial value of homogenous post consumer polymers command a higher price on the global market. Collection costs are also reduced by the use of automated systems as increased compaction of materials during collection can be made as through flow and identification rates at MRFs can be increased. The use of automated separation systems may also enable the collection, identification and separation of other household plastic products to become more viable, increasing the amount of plastics reclaimed from the domestic waste stream. Manual separation has been stated to be a limiting factor in this practice by trials conducted by NSR Sweden.

Innovation and developments in polymer identification and separation for WEEE and ELV plastics have demonstrated and enabled the ability to separate more plastics for mechanical recycling from these products. Increasing amounts of plastics are being utilized within these sectors, especially in the automotive industry where weight savings increase fuel efficiency which is becoming a major selling point as fuel prices increase. As weight based recycling targets have been applied to these sectors through the pertinent Directives, based on the weight of the whole product and not on specific materials, if more plastics are to be utilized in the initial construction then the means for which to recycle them require being available and in place. The main regions developing such processes appear to be in the Netherlands, Austria, Belgium and Germany with vehicle manufacturers such as VW contributing R&D and investment into their establishment.

Economic aspects

In order for recycling to expand, the financial cost of collecting, separating and recycling plastics has to be consistently cheaper than alternative waste management options. Landfill and incineration has, and remains in many regions, a cheaper alternative. However the introduction of landfill and incineration taxes has enabled recycling to become cost competitive for certain polymer types and in certain regions.

The economic viability of mechanical material recycling remains strongly dependent upon the price of virgin polymer materials which, although high at present, remains fluctuant over time and may fall in the near future. It has been stated by a number of recycling companies interviewed that demand for recyclate is fairly high at present due to current virgin polymer prices. However a number of factors are affecting the wider use and demand for recycled material.

Although automated identification and separation techniques are available and their benefits have been discussed, the main “bottleneck” in plastics recycling system remains to be in polymer specific identification and separation. Instability in market demand, the price obtainable for post use plastics, and risks associated with return on investment appear to be limiting the wider adoption of such equipment. This situation appears to be amplified in the UK packaging recovery system where the market based PRN system is utilized to financially aid such investments. Due to volatility in polymer prices as well as that of PRN revenue, these combined uncertainties are affecting the willingness and ability for waste management operators to justifiably invest in equipment. Price volatility affects a number of other countries and may lead to a lack of investment in a number of technologies and innovations further inhibiting market development. However evidence from Germany in particular has proven that investment in large scale automated systems does provide return on investment within approximately three years. Within the German situation a combination of factors is allowing this including a ban on landfill and a well establish collection system with financial capability to aid investment.

Other factors affecting the wider establishment of automated systems include:

- Automated separation systems, although developing and have been commercially operating for some years, are still generally in their infancy and remain fairly costly investments to make.
- Relatively high volumes of material throughput are required (>10,000tonnes/year) in order to achieve economic viability and secure returns on investment. However this can be overcome through inter-regional or cross-border cooperation such is the case in Norway which utilizes Denmark's capacity and capability in this sector. Both regions/countries therefore benefit from economies of scale. This also aids the recycling industries by aiding the supply of an increased volume of material securing the volumes of supply required to ensure and secure market demand.
- The current high demand for mixed polymer waste from foreign re-processors, in particular India and China, where lower labour costs enable manual separation of polymer types is also seen as the 'least cost' alternative to investing in automated and increased manual separation methods.
- Limitations to technology also affect the effectiveness of the most commonly utilized and available identification system. The fact that Near Infra-red spectroscopy can not identify the polymer type of black and dark pigmented plastics is a limiting factor. The fact that coloured and printed recycled materials are often black as well as a number of food tray packaging of various polymer types including PS, PET and PP being black makes identification difficult. This can be over come through the combination of NIR and optical/image identification along with manual quality control although this increases the cost base. Alternatively feedstock and chemical recycling capacity which can overcome these barriers requires to be developed.

Within the ELV and WEEE sectors, the investment issues in identification and separation systems are also apparent (although limited information was obtained from this sector). These mainly relate to increasing labour costs, automated system technology infancy and development/establishment costs. The greater volumes of engineering plastics utilized in these sectors, including ABS and PC, result in the economics of recycling becoming more advantageous than for large-volume commodity thermoplastics and therefore the costs associated with separation become more favourable provided that markets are available. This also enables the use of more expensive identification techniques such as sliding spark spectrometry which overcome the limitations associated with black and coated polymer identification by NIR. Due to the multi material (metals, plastics, liquids etc) nature of these products and the presence of substances of concern, the international trade issue is not as apparent due to the TFS regulation stipulations. However there appears to be a fairly substantial grey area/illegal trade in such goods for recycling that requires to be addressed.

International trade

International trade in plastics including virgin resins, post consumer products and regranulate is an economic issue based on free market principles. However as this has been implicitly specified as the main concern for plastics recyclers in Western Europe it warrants specific consideration.

Increasing industrialisation and demand for commodities such as plastics along with lower processing costs in countries such as India and China are stimulating a growth in the export of post use plastics. As there is a net export in trade from these countries to Europe the environmental burden from shipping would not appear to be amplified above and beyond normal operations. The shipping of such materials is cheap due to otherwise empty containers returning to the East being utilized with some goods, adding to the ballast that would otherwise be achieved through carrying ballast waters. This trend does have a variety of implications on recycling practices in Western Europe. The benefits associated with such trade are apparent. There is obviously demand and established and functioning markets for recyclate in these countries which may not be as established within Western Europe. Lower labour costs enable low cost identification and separation of plastics into homogenous polymer fractions making the economics of recycling more viable. Investments in capacity are being made by domestic (i.e. Indian and Chinese), European, and other such as Australian, USA and Japanese based companies to develop large scale recycling industries in Pacific Rim countries, especially China and India enabling substantial economies of scale to be achieved as post use plastics is obtained from a number of countries. As manufacturing activities expand in these countries, producing products for the European markets, recycled plastics may be returned to the European consumer cycle in such products.

On the flip side a number of issues arise. With a viable global market existing for mixed polymer waste (although demand is primarily for PET, PE and PP), the incentive to invest in or carry out separation domestically, prior to export, is reduced. Investment in separation within in a number of regions throughout Europe is not being made to the extent required, as collection volumes increase the ability to reduce the levels of contamination as defined by the TFS regulations (anything that inhibits the recycling of the material) is being impeded. It is therefore likely that contaminants, in violation of TFS regulations, or undesirable polymer types such as PVC may enter the waste shipment consignments and end up having to be disposed, and not recycled, in the country of destination. Due to the availability of plastics from Europe which is establishing increasing collection rates and the low cost of shipping and obtaining materials, the incentive to collect post consumer plastics in the receiving countries is diminished. This has been stated as a main concern of exporting recyclables as it provides little incentive for countries such as China and India to transition up the waste hierarchy with their domestically produced waste and therefore landfills and indiscriminate dumping are increasing (Duraiappah, *et al.,* 1999). A UK specific impact is that high demand, bringing PRN prices down, provides producers with little financial incentive for minimising waste and evaluating which packaging materials are preferable from a waste management perspective.

However, homogenous polymers do command a higher price on the international market acting as an incentive for separation. The main impact of international trade from this point of view is the pull of material out of Europe limiting the critical mass of material available for domestic re-processors. This makes it difficult for domestic recyclers to establish viable markets as the availability of materials shall fluctuate with foreign demand. This may also discourage research and development activities into the use of recycled materials within domestic markets. The reverse situation may occur however as competition on the open market may encourage further innovation and result in more effective and cost efficient processes.

The consequence of foreign markets collapsing is a risk, the impact of which shall dramatically affect domestic ability to meet recycling targets. In recent years countries such as India and China have had high demand for post use plastics and regranulate due to their domestic virgin polymer production capacity being lower than demand for materials. Therefore these countries relied upon imports of both virgin and post use plastics inorder to meet domestic demands. However production capacities is being established to meet the shortfall in demand and are beginning to export virgin polymers to Europe, USA and other countries as their domestic production capacity meets and surpasses domestic requirements. This may have an impact on the market demand for post consumer plastics from European nations in the coming years (Duraiappah *et al.,* 1999; CIWMB, 2003).

Waste shipment consignments in breach of the transfrontier shipment of waste regulations are also a major concern at present. Where mixed MSW have been appearing in shipments investigated by IMPEL is a reflection of the lack in domestic separation investment. It has been suggested that China is likely to impose stricter controls on waste consignments entering the country in the near future (ECOLAS-PIRA, 2005). This may initially impact certain European collection systems that are currently heavily reliant upon mixed polymer export to meet recycling targets such as the UK. This further emphasises the fact that investment, and the means of financing in order to invest in better separation (particularly automated separation if collection volumes are to be increased to ensure targets are to be met) is essential.

Social, institutional and organisational aspects

Governmental institutions have had a marked impact on recycling by intervening in free market forces through the introduction of various policies. Without intervention landfill would likely remain the cheapest and therefore dominant waste disposal option with greater environmental burden than today.

The REACH framework and RoHS legislation being introduced by the EU shall likely benefit and enable further recycling of plastics that are presently difficult to recycle due to the additives and substances contained within them. However historical waste shall remain in the waste stream for some time, particularly within PVC from the building and construction industry and longer life EEE equipment (including those stored and not discarded) and shall continue to pose a challenge to plastics waste management. Developments in technology and techniques that enable the extraction of substances of concern such as heavy metals, polychlorinated biphenyls, brominated flame retardants etc are emerging. However as bans on such substances are introduced, if methods for removing them are not in place, the recycling of such material is likely to end and alternative treatment options shall be required.

Information gaps exist between the plastics recycling industry and the plastic product manufacturing industry. It has been stated that plastics product manufacturers regularly approach recycling companies enquiring about materials and stipulating high material specifications. This also indicates that producers lack the knowledge regarding where recycled products can be utilized and their potential benefit. Plastic product manufacturers within Western Europe have also stated that they are increasingly relying upon quality of product to compete with cheaper product imports and foreign processors. Therefore in order to promote and establish high grade markets for recyclate quality assurance is required. Quality standards for recycled materials and the development of low cost or centralized testing procedures to provide industry with quality assurance appears to be lacking and are essential and required if markets are to be established and secured.

Selective collection of plastics suitable for mechanical recycling form MSW and other waste streams may ease the burden on polymer identification and separation. However, this shall require increased dissemination of information and knowledge to consumers to obtain the required polymers. This may also result in less plastics being collected both for mechanical recycling due to uncertainty and mixed information and for feedstock and other advanced recycling which may be available for mixed and non-recyclable plastics. A combination of systems appears to be justifiable from many respects. The selective collection of food contact PET through one system, such as deposit refund or similar, obtains foodstuff packaging fit for beverage bottle to bottle recycling. A kerbside collection system for other municipal plastics can enable the collection of other plastics. Optical and image separation can also enable food packaging to be obtained from mixed plastic sources, however the quality and source will not be highly guaranteed.

Summary

There are a number of limitations associated with mechanical recycling including:

- Detrimental additives in certain plastics and products which adversely affect the recyclate properties and/or human health and safety (particularly with regard to recycling plant employees);
- Health and safety issues related to recyclate utilized in food contact packaging;
- Different polymers being incompatible in recycling processes, which, even with compatibilizers, limits the recycling of many materials including co-polymers and multi-polymer layered material;
- Lack of polymer specific identification and separation capacity limiting the volumes of homogenous post consumer plastics available to domestic recyclers especially;
- Contaminant issues which degrade the quality and melt flow characteristics of regranulate;
- Colour and quality assurance issues,
- Technical limitations including heat and shear degradation restricting melt re-processing to approximately nine cycles;
- Collection infrastructure and public participation in recycling remain limited in certain regions;
- Knowledge transfer and diffusion between all actors in product life cycles, a disconnection between recyclers and product manufacturers appears apparent;
- Fluctuant and volatile virgin and post use polymer prices and demand from foreign re-processors affects material availability and costs.

Drivers/ opportunities

- Technology advances and innovation, particularly in separation technologies, food contact recycling processes, and processing techniques enabling better quality recyclate and new markets to be created;
- Increasing fossil mineral prices increasing the economics and market demand for recyclate;
- Policy intervention in a number of areas including: landfill taxes, bans and operational requirements increasing the financial costs of landfill and making alternatives more attractive; recycling targets and EPR policies influencing product design and aiding the financing and development of collection and separation systems;
- Political and industry commitments to phasing out detrimental additives from plastics and specific products.
- International cooperation can aid achieve economies of scale and cost reductions for: separation (i.e. separation taking place in low cost nations, or by automated separation within Europe at a number of centralized locations (e.g. the Norwegian-Danish cooperation)); and recycling through large scale recycling in globally centralized locations such as India and China. However there are inherent issues with relying upon low cost nation capacity.
- Increased information flows and integration of material recyclers and the manufacturing sectors to encourage further market development

7.3 Advanced Recovery Technologies

Advanced recovery options, having seen a period of stagnation and a down turn in their utilisation since the initial establishment in the early 1990's, now appear to be attracting renewed interest. This is a result of a number of factors including innovation and technology advances; increased collection infrastructure developing throughout Europe with associated identification, separation, mechanical recycling technology, market outlet and contamination limitations; and recycling/recovery targets requiring to be met through a variety of means.

Technological innovation aspects

Technological advances and innovation as well as previously available, though not commercially realized, technologies being increasingly proven in the global arena are aiding investment in new advanced recovery technologies within Western Europe. Chemical recycling is in operation for polyamides and capacity is due to develop further if the PET chemical recycling plant being constructed in Italy develops to commercialisation. Feedstock and chemical recycling do offer a number of advantages over mechanical recycling due to certain processes being capable of overcoming limitations such as contamination, colour of resultant product and loss of melt flow properties. Polymer cracking has also been proven to produce virgin quality homogenous polymers from mixed polymer wastes. However a number of factors impact their wider establishment and adoption as well as greater energy consumption necessary within these processes in comparison to mechanical recycling with associated cost and environmental burden.

The risks associated with innovative technologies entering commercialisation as introduced in section 6.2.2.4 do affect advanced and other recovery/recycling technologies and require to be taken into account by stakeholders.

The *technology risks* [relating to whether the process will achieve expected performance levels, efficiency improvements and cost reductions when scaled up from pilot to full scale industrial processes] has been shown to affect a number of advanced recovery technologies. The RGS90 PVC recycling plant, although proven on a pilot scale has been partly inhibited from realising full commercialisation by pre-treatment difficulties and other technical constraints. The same is apparent with the Solvay Vinyloop process and may also potentially affect emerging technologies (e.g. the project POLSCO polymer cracking process if invested in and scaled up) given the experiences of these processes.

The *market risk* [concerning the uncertainty of future levels of return for product produced] is affecting the establishment of a number of technologies including mechanical and advanced recycling. The project POLSCO polymer cracking process in particular would be very reliant upon the volatile price of crude oil and the variable income associated with the UK's PRN revenue. Therefore the period of return on investment could not be guaranteed and has likely contributed to this process remaining as a proven though as yet not commercialized technology.

The *Regulatory risk* [where markets are created by policy mechanisms associated risks are taken due to the fact that social institution priorities or governing parties may change] is also prevalent. The RGS90 PVC chemical recycling plant is an indication of this risk. The premise on which this plant was constructed largely related to the proposals by the EU to introduce PVC waste legislation. However, as these proposals have since been dropped and the collection and stipulated treatment is not being undertaken throughout Europe as anticipated, the material available for treatment has not been obtainable. Along with the technical difficulties associated with this process and the unfavourable economics of development and operation (resulting in the process not being able to compete with incineration, landfill and mechanical recycling on financial grounds), it is unlikely, at present, that the facility shall become commercialized.

Also associated with regulatory risk are the 'grey' areas that exist in the definition and classification of what constitutes recycling and that which is recovery. As there are grey areas that exist in policy definitions regarding these, which may likely be amended and expanded upon in the future, there is a risk that a technology that is regarded as 'recycling' today may in the future be regarded as 'recovery'. This may affect the investment in, and development of, such technologies due to uncertainty surrounding which legislative defined target they shall meet. Therefore there requires being a firm political stance with well defined objectives in conjunction with common, harmonised and updated definitions to facilitate and stimulate secure development, innovation and investment.

Economic aspects

A major factor affecting the viability and further adoption of advanced recovery options is economics. These facilities require being cost competitive with alternative treatment options and the development and operational costs require a secure and guaranteed rate of return on investment. The majority of processes which are capable of material recycling through depolymerization and subsequent repolymerization are not, as yet, economically viable, particularly for commodity plastics. This is again due to the variable and volatile price of virgin materials, which, although being high at present in comparison with historical trends, are still low, or collection and processing technologies are too expensive, to justify investment in a number of processes.

The recovery of plastics in blast furnaces and cement kilns reduces associated development costs by utilising existing processes constructed for the production of other materials. Therefore the economics of treating plastics via these means have financial benefit both for waste management and the production facilities that obtain valuable resources to substitute conventional fuel sources at reduced cost or potentially financial gain. However the use of such facilities is largely restricted to the vicinity in which existing plants are operational, and rely on such facilities making investment in pre-treatment and feed systems.

The fact that pre-treatment of waste, in order to obtain either a homogenous polymer source or hetrogenous mixed polymer without other materials and limited contamination (levels accepted vary depending on process), is required increases the associated price in comparison to MSW incineration which accepts commingled wastes. However policy intervention with stipulated material recovery rates are aiding and encouraging the separate collection and EPR schemes are further aiding in reducing the associated cost burden on local authorities.

The SVZ gasification methanolysis plant also benefits from not having to rely upon plastics waste specifically for which to operate. This results in a situation whereby if plastics are diverted to alternative processes the associated risk to SVZ is reduced, as feed materials can be substituted with alternative resources. Greater economies of scale can also be achieved through the use of various fractions as reliance and the risk associated with operating on a single material is again reduced.

The economics of Ozmotech's Thermofuel system look promising in comparison to other commodity plastic specific advanced treatment options. The cost reductions achieved by benefiting from economies of scale in production are an important factor. The fact that a synthetic diesel is produced to road fuel standards also reduces investment costs in establishing an on-site energy recovery process (generators can however be integrated into the design to produce up to 1.4Mwh of electrical power from 10 tonnes of plastic per day). The market demand and price obtainable for diesel fuel remains relatively constant over time potentially guaranteeing a steady income. However, it remains to be seen if supply of materials and pre-treatment requirements can be achieved. The scale of the proposed facilities (20 tonnes/day equating to ~7 000 tonnes/year) is considerably smaller than current advanced recovery methods and MSW incineration plants. Therefore the risk that plastics are diverted from material recycling would not appear to be a major issue. PET and PVC are required to be separated prior to this process, thus, for packaging waste, prior separation is required and materials can be reclaimed for mechanical recycling prior to the processing within the plant.

Social, institutional and organisational aspects

The main concern raised by the developers of the Thermofuel process in the UK and Ireland was the time and investment needed in achieving planning approval for sighting facilities. This has also been raised by recycling industries and other EfW plant developers throughout Europe. There is undoubted justification for conducting Environmental Impact Assessments and having public consultation. However the main concern surrounds political unwillingness to commit to projects. This 'Not In My Term of Office' and NIMBYism can hinder even the most appropriate developments for waste management infrastructure in any region. With the planning process reportedly being in excess of three years in some locations in the UK, process developers are increasingly being put off investing time in developing recycling and recovery processes domestically and instead invest in foreign countries where construction can begin immediately (Connelly & Maitland pers comm., 2005). There is therefore a need for politicians and planners to make strong commitments to development in infrastructure and capacity in order to meet targets and create a more sustainable society if a transition away from landfill is to be achieved. This should be done by streamlining existing procedures and not by compromising environmental and social impact assessments. The general public, politicians, and local councils should be aware of the costs and benefits of such developments and be fully educated of the implications, which in certain regions, appears to be lacking.

The advanced recovery options in operation, and being established, do provide advantages over large scale incineration and landfill. Higher recovery efficiency than conventional EfW incineration is achieved. Generally these options also have smaller capacities and material throughput than EfW incineration and therefore the impact of transportation on the local society is less, potentially making them socially more acceptable. Processes such as the Thermafuel system have the potential to provide a relatively small scale, localized recovery option, for residual plastics derived from MSW and other waste stream collection systems. This may encourage further collection and separation to be developed given that a viable market shall be established and increased demand for plastics shall develop. Experience from Norway, Sweden and Germany illustrate that not all plastics collected from such schemes can be mechanically recycled. Due to the lack of MSW incineration capacity in certain regions and countries, and development issues associated with establishing such facilities, small scale recovery options are likely to be beneficial. This shall potentially aid the transition up the waste hierarchy for a number of waste streams and encourage increased separate collection of plastics from a number of sectors.

With limitations associated with the mechanical recycling of PVC (detailed in appendix 5), and the fact that most advanced recycling technologies can not treat PVC, the prospect that the RGS90 chemical recycling plant is unlikely to reach commercialisation makes PVC likely to remain a contentious issue. The main alternatives remain to be incineration or landfill.

Summary

Advanced recovery options are developing and have great potential in the plastics waste management sector. However there remain factors that inhibit their wider use:

- Inherent risks to investment exist, particularly in relation to price volatility of raw and post consumer materials. High energy and process costs are associated with most advanced recycling technologies. Economics therefore remain the limiting factor and main barrier to further investment;
- Securing supply and critical mass of post consumer materials (particularly of low chlorine content) at appropriate price to cover investment costs can be a limiting factor especially if processes are reliant upon single materials and sources;
- Energy savings and overall environmental gain are less than with mechanical recycling;
- Establishment and development process can be substantial and social acceptance over mechanical recycling can be a barrier to commercial development.
- At present no advanced back to polymer material recycling methods are in operation within Western Europe for commodity plastics. However processes for engineering resins (i.e. polyamide) are in operation and chemical recycling of PET-to-PET is likely to become established in Italy relatively soon.

Drivers and opportunities

- Proven technology exists and innovation in technology developments are increasing;
- Smaller scale and more efficient recovery technologies are being developed and entering the market;

- Market demand for products produced through advanced recovery options is not a major issue as high grade products including methanol, diesel, electricity, and virgin grade polymer intermediates, monomers and polymers can be produced;
- Mixed plastics can be treated in some processes as well as contamination being of lower concern than in mechanical recycling, the limitations associated with mechanical recycling are therefore substantially removed, although economically mechanical recycling remains more viable at present;
- Increasing fossil mineral resources and other commodities may stimulate further investment and create a situation whereby economics become favourable for back-to-monomer/polymer feedstock or chemical recycling of commodity plastics.

7.4 Incineration with Energy recovery

EfW Incineration capacity is increasing throughout Western Europe as the waste management industry goes through profound changes and regions develop and implement strategies to move away from direct disposal. Although incineration has not been reviewed in-depth within this report, this recovery option does have an important role to play in an integrated waste management system. However a number of factors have been identified and require to be taken into consideration.

Mass burn and fluidised bed incineration are proven and well established technologies. Research and development into thermal recovery efficiency optimisation does continue. However, the majority of waste incineration plants in operation at present have relatively low thermal recovery rates (average 30%). Retrofitting existing facilities to improve recovery rates have been determined to be largely economically unviable at present (Wollny & Schmied 2000). New facilities do benefit from technology developments and potentially increased thermal recovery rates although infrastructure development costs associated with installing district heating which optimise thermal recovery are high and guaranteed waste flow and volume is required to recuperate costs. Minimum recovery efficiency standards may however encourage investment and potentially make alternatives such as mechanical and advanced recycling financially more attractive with associated environmental benefits. At present this is utilized in Norway to ensure recovery of plastics packaging is optimised by stipulations that incineration requires to have a 50% thermal recovery rate in order to be deemed as recovery. More precise definitions on what equates as recovery is therefore required to be adopted at a European level with minimum energy recovery rates stated to encourage the more resource efficient use of waste and aid a transition up the hierarchy.

The stipulations of the Waste Incineration and IPPC Directives along with concerns from non-governmental interest groups and industrial R&D have, and continue, to encouraged developments in emission control technologies to lesson the associated environmental and health impacts. Advanced recovery technologies are required to comply with these stipulations also, however commingled waste incineration facilities are larger scale than mono-material or advanced recovery options. Pollution abatement equipment is therefore generally larger and installed to control a larger volume and variety of emissions. This is providing a viable alternative recovery route to recycling and advanced recovery options that are not capable of accepting chlorine rich plastics such as PVC, brominated plastics, and materials containing other substances of concern. The removal of such plastics from society via combustion is potentially beneficial, for as detrimental additives are removed, recycling in the future is likely to benefit.

Limited capacity and potential to recycle and recover thermosets and composite plastics by mechanical or advanced recycling methods exists within Europe at present. Therefore EfW incineration provides a viable option for these materials. Developments have been made in processes to reclaim composite fibres from incineration plants however the low volumes of composites and the degradation of fibres within this process suggest that investment in such recovery installations shall remain limited. Cement kilns also provide an alternative recovery option for these materials provided boron is not present significant quantities.

Due to commingled waste acceptance at such facilities, less separation is required and high compaction of materials within collection vehicles can be achieved reducing collection burdens particularly in rural areas. However incineration requires large investment in order to establish new facilities requiring substantial investment and commitment from local authorities or public/private partnerships. There is a risk that such large scale incineration which requires guaranteed waste input may cause a diversion of materials from alternative treatment options further up the waste hierarchy if the gate charge is lower than alternatives. However 'waste' can potentially be substituted with biomass if plastics and other waste resources establish alternative markets. With continual development in thermal treatment innovations, it is reasonable to include EfW incineration in an integrated waste management strategy. In order to avoid the situation where recycling cannot compete with incineration the introduction of national/international incentives (taxes (on both landfill and incineration), command and control requirements etc.) may be required, if the benefits out way the total costs. It is important that new incineration plants are dimensioned for the right waste flow, i.e. only residual waste (after the recyclables have been reclaimed) if the material recycling market is to grow and establish itself, further stimulating a transition up the waste hierarchy.

Public and social intuition objection and opposition to the establishment of new municipal incineration plants remains a crucial factor in their establishment in many European countries. This may stimulate developments in alternative recycling and recovery options although the ability to collect and recover all plastics or other wastes from the various waste streams and residual waste fractions shall require to be dealt with by other means, most likely by landfill as the main alternative for such mixed residual wastes. However commingled pyrolysis, gasification and autoclave processes, although out with the scope of this study, are emerging alternative options that are beginning to be establishing in some regions within Europe.

International trade and inter-European trade in waste for incineration are limited due to the self sufficiency principal within the Waste Framework Directive (WFD) and the TFS regulation stipulations. However in light of Germany's recent declassification of MBT residue as waste, and reclassification as a 'non-waste' Solid Recovered Fuel (SRF) along with the WFD revisions proposing a similar classification, the trade in such materials may increase. This has already been seen in Germany which has begun to export such SRF to Eastern Europe (ENDS, 2005f).

This has important implications on whether development of new waste specific incineration plants shall be required to the extent proposed in many National Waste Strategy documents, or whether existing power stations can utilize this fuel without modification to comply with the waste incineration directive. The proposals for the revised WFD indicate that the SRF, and not the power plant, may have to comply with standards concerning the calorific value, chlorine and mercury content (ENDS, 2005f). This shall require that PVC and WEEE products, along with other materials with potentially detrimental additives such as brominated flame retardants are removed. However, plastics that are not removed for recycling shall likely remain in SRF.

With investments being made in MBT facilities in a number of European countries this may aid the transition away from disposal without the economic burden and local objection to MSW incineration plants. This may be limited to localities where existing power plants with the capability to accept refuse derived fuels exist although with out the need to recuperate investment costs through gate charges, the economics may allow or even encourage further transportation distances.

The implications of such a decision may affect further investment and development of certain advanced recovery technologies. Although these routes can result in (plastic-to-plastic) material recycling, the main processes in utilisation today, including the SVZ plant, blast furnaces, cement kilns and the emerging thermofuel process, are generally classified as recovery options or 'grey' areas. This may have an impact on such technologies in sourcing plastics unsuitable for mechanical recycling though suitable for these processes. Therefore minimum recovery rate efficiency criteria should be set in order to ensure the maximum resource use is achieved. The use of co-combustion does mean that a guaranteed waste stream is not required to fuel the plant and therefore as markets, innovation and alternative treatment capacities develop, the removal of material fractions from the SRF shall not impact energy recovery rates as alternative fuel sources can be utilized to substitute waste feeds.

Summary

Incineration with energy recovery remains a viable alternative to landfill due to the ability to accept commingled wastes and recover energy value. The ability to capture and remove detrimental additives from the production cycle whilst recovering energy from the material in which these additives are contained can be advantageous to landfill. However, many substances of concern are required to be disposed of in landfill within fly ash residues. Developments in improving thermal recovery efficiency are being made, however incineration should be scaled and remain an option for residual waste only, if a transition up the waste hierarchy is to be made. It is clear that if material recycling is to be given preference in order to transition further up the waste hierarchy, the financial cost of recycling has to be competitive with that of energy recovery.

8. Conclusions and Recommendations

Within this final chapter the original research questions shall be reflected upon and answered drawing from the concepts and findings addressed throughout the paper.

The main goal of this research was to investigate and determine the present condition, developments and trends occurring in the end-of-life management of plastics arising within Western European waste streams. Furthermore an attempt to identify the drivers, barriers and other factors influencing a move away from direct disposal and aiding a transition up the waste management hierarchy has been undertaken. What is clear from the research is that a vast amount of plastics waste is produced annually within the Western European geographic region. 21 Million Tonnes of plastics waste were produced in 2002 and this figure continues to rise. There is a clear need to reduce this volume and conserve resources, material recycling is one way in which resource conservation can be achieved, however there are inherent issues associated with such practices.

Due to the variety of polymers, their incompatibility with other polymer types in melt recycling, and the amount and variety of additives utilized to provide a range of properties, plastics are inherently difficult and or expensive to recycle. Low weight to volume ratios and the range of applications and products in which they are utilized increases the cost and practicalities associated with collection and separation. However developments are taking place in order to collect and treat a number of plastic wastes from various sources.

It is apparent that, in order to make full use of the resources available from post use plastics materials, no one solution is available. The plastics industry as a whole, from virgin polymer production and processing techniques (including new compositions and material properties), through policies and political intervention affecting the whole life cycle, to plastics recycling and markets for recyclate are constantly evolving in a rapid and dynamic way. Therefore there is a need to continuously re-evaluate the way in which society as a whole utilises these materials throughout their life cycle. An integration of the various waste/resource management options, technologies and techniques available, evaluated for fitness of use on a case by case basis taking into account economic, social and political factors is required to move away from disposal and transition up the waste hierarchy as developments take place.

Throughout this research project three research questions have been addressed.

RQ1. *What technologies are currently available and on what scale are they being utilized within Western Europe for the recovery and recycling of plastics waste?*

It has been identified that capacity is increasing for all forms of recovery from mechanical material recycling, to energy recovery incineration across Western Europe. Mechanical recycling is the dominant material recycling route although only 12% (2.5 Million of the 21 Million tonnes) of plastics waste arising was reportedly recycled by this means in 2002. The main polymers recycled are Industrial distribution packaging including PE and PP films, crates and drums; agricultural films; and PET and HDPE beverage bottles. The main expanding and developing sectors are in ELV and WEEE commodity and engineering thermoplastics as well as other municipal packaging applications. Capacity to recycle far more within Western Europe does exist with an estimated 40% of current capacity not being utilized mainly due to a lack of homogenous materials and to a lesser extent market demand. Closed loop recycling of PET Beverage bottles has developed significantly in recent years. This increased from

36,000 tonnes in 2002 to 67,000 tonnes in 2003 and is rapidly expanding as investment in technology capable of achieving food contact certified material recyclate is made.

The limitations associated with mechanical recycling and increasing volumes of post consumer plastics being collected are giving rise to more material volumes requiring alternative recovery processes. Advanced recovery technologies (including feedstock and chemical recycling) are experiencing a renewed interest after a period of stagnation in such processes entering into commercial operation in the late 90's and early 2000's. This is due to a number of factors including EU wide policy intervention setting recycling and recovery targets for a number of waste streams and increasing the costs of alternatives such as landfilling. At present however only polyamide is material recycled through non-mechanical recycling means to any significant extent. Methanol is also produced through gasification feedstock recycling of plastics in Germany and growing use in blast furnace applications as a reducing agent in pig iron production is being seen. The majority of recovery however is achieved within MSW energy from waste incineration plants with cement kilns also constituting a small percentage of energy recovery.

RQ2. ***What developments are taking place and what are the identifiable drivers and barriers to establishing further plastics recycling and recovery within the Western European geographical region?***

DRIVERS

Policy and social factors

A number of policy instruments and initiatives have been, and are being developed in the EU and individual member states that are encouraging recycling and a transition up the waste hierarchy. Public awareness campaigns continue to influence the public involvement in such issues driving further collection and recycling of plastics. European wide and country specific programmes are being developed and implemented so as to stimulate the development of efficient and effective waste management operations throughout the regions, resulting in immense and profound changes in the waste management sector throughout Western Europe and the wider European Union region. Landfill is becoming more expensive due to the landfill directive stipulations, landfill taxes and bans on certain wastes going to such disposal. Recycling targets are encouraging more collection of recyclable plastics with industrial distribution packaging and agricultural films providing the main collected and recycled materials.

Increasing information and knowledge being disseminated from recyclers and collection companies to industry and householders is improving collection rates and quality of materials. Clear information as to the requirements and benefits of proper source separation are essential so as to obtain the volumes of uncontaminated and high quality materials available from consumers. Knowledge regarding there issues is increasing and has been found to be a key driver in acquiring the materials sought by recyclers, however there appears to a number of areas where increased information is required.

Technological factors

In terms of increasing recycling rates from the current levels being achieved in the WEEE, ELV and MSW sectors especially, the most important developments is in separation technologies. Advances in automated identification and separation techniques are aiding greater amounts of homogenous plastics from the municipal, automotive and electrical and electronic industries to be obtained for mechanical recycling. The development in such techniques for automotive shredder light fractions shall substantially aid the recovery of polymers from ELVs and WEEE sectors where plastics use is increasing.

Technology advances in mechanical recycling processes capable of producing PET regranulate suitable for use in direct contact with foodstuffs packaging are also aiding closed loop recycling of such polymers and the development of high end markets for recyclate which is environmentally preferable in material resource utilisation and energy consumption terms. Advances in compatibilizers and polymer blending (blending a mix of recycled polymers or a mix of virgin and recycled polymers) techniques are also enabling improved material properties to be produced from mixed polymer recyclate thereby aiding the variety and quality of products produced from such recyclate.

Small scale advanced recovery processes capable of producing electricity, thermal recovery and/or transportable synthetic fuel are also emerging providing localized recovery options for relatively small volumes of materials that are otherwise unsuitable for mechanical recycling without the need for high investment in large scale recovery facilities. This is particularly potentially beneficial in regions where other energy recovery facilities are not available.

Economic factors

Other factors driving plastics recycling and recovery include rising virgin polymer prices. Due to fossil mineral resource price increases, including for feedstock and production energy requirements, virgin grade plastic prices have been increasing dramatically over the past year and aid the development of markets for recyclate as manufacturers look for cheaper material alternatives. The higher market value obtainable for recyclate is also aiding the economics of collection, separation and recycling to become more attractive options to waste managers.

The demands for post use plastics and regranulate from the Pacific Rim countries (in particular China and India) and the investment and development in recycling capacity in such countries are producing viable established markets for materials. With post use plastics being a globally traded commodity, market competition for these resources are resulting in increasing prices being paid for collected materials, providing further incentives for separate collection of recyclables from various waste streams.

BARRIERS

One of the major barriers (once collection schemes are operational) to the wider utilization of recyclate within Western Europe, is the lack of quality assurance standards and testing procedures available to small to medium sized recycling businesses at reasonable cost to provide the quality assurance required by product manufacturers. Domestic plastic product manufacturers have stated that quality aspects are increasingly becoming their main selling point over cheap imports of goods and therefore require quality assurance.

A lack of information and knowledge exchange between the recycling industry and product manufacturers is also apparent and preventing the wider adoption of recyclate by domestic producers. There is a requirement for product manufacturers to realize where recycled plastics materials can be utilized and the benefits which they can bring if markets are to develop further and domestic recycling is to increase.

Variable and volatile polymer prices do present an inherent challenge to plastics recycling as large investments in recycling and separation technologies can not guarantee return rates. This shall continue to hinder further investment unless secure markets for recyclate are achieved and the means for which to invest in such technologies are made available.

Polymer cracking material recycling has been proven and does potentially offer the most viable option due to its relative robustness to contaminants in comparison to other material recycling methods. This also enables the conservation of material resources to a higher degree than any alternatives in the long term (given that polymers degrade to an unusable extent after nine mechanical recycling cycles which is not the case with feedstock and chemical recycling). This process does however require more energy resources in order to depolymerise and repolymerise the materials and mechanical recycling is therefore preferable. The economics of developing and establishing such a process to industrial commercialisation, cost competitiveness with alternative processes, and the volatile rates of return from product are however preventing investment at present.

The export of mixed waste (mixed polymer waste and the grey to black market trading in mixed polymer/paper etc waste) commanding a relatively high price on the international market without the need for prior separation is also affecting the domestic recycling industry. This, in certain regions, is resulting in a lack of investment in polymer identification and separation technologies which are essential if collection volumes and types of plastics waste are to increase and be recycled. The lack of domestic identification and separation technology is having a profound affect on recycling operations and businesses in certain regions and adversely affects the ability to establish and promote domestic markets in recycled materials.

BIO-POLYMER DEVELOPMENTS

The growth and developments in renewable raw material based polymers is potentially the most important development within the plastics industry. Brought on by increasing realisation that a dependence on finite fossil mineral resources is not sustainable and the economics associated with their use becoming more favourable due to increasing production capacity and growing petrochemical polymer prices. However these materials still occupy niche markets in the packaging and agricultural sector and in 2004 represented a mere 0.001% of the total plastics consumption within Western Europe. Even though rapid developments are taking place and production is set to increase over the coming years, the promotion and market demand for these materials should be encouraged as they offer substantial benefits over petrochemical based polymers. For this to take place, the establishment of effective collection, separation and treatment infrastructure is essential, so as bio-polymers do not enter and inhibit conventional plastic material recycling.

RQ3. *What are the implications of the identified developments, drivers and barriers on plastics waste management in Europe moving away from disposal and how can these enable, or be overcome to aid, a transition up the waste management hierarchy?*

The implications of the developments have been discussed in chapter 7. It is clear that there is no one process or option available for the recycling of all plastics at present due to the vast number of polymer types and additives utilized. The most appropriate option, from an environmental and economic stance, for the recovery of plastics from various waste streams is also regionally and often product sector specific. Therefore an integration of methods is required so as to result in the socially optimal (optimal in terms of economic, environmental, local population, and political points of view) management system.

The development of small scale recovery options such as the thermofuel process have the potential to enable residual material obtained from various collection and separation systems to be recovered without the need for large scale investments and developments in MSW incineration or similar large scale processes. Due to the feed requiring to be exclusively plastic, this shall likely encourage further establishment and pull of plastics from various collection systems.

Increasing PET bottle-to-bottle recycling and research and developments into other closed loop food packaging recycling has important implications on diverting a large quantity of plastics from landfill and utilizing the resources effectively as foodstuff packaging represents a large proportion of plastics waste arising. However it is important that bio-polymer development is not inhibited by petrochemical based plastics recycling investments and collection infrastructure.

Recycling targets are promoting the further collection and recycling of plastics from many sectors and EPR systems are aiding the supply of materials to the recycling industries either through take back schemes or financial contributions from the producers. However plastics consumption and waste production continues to rise year on year and there is a clear requirement for promotion of waste minimisation.

The REACH framework and RoHS Directives shall likely have the impact of reducing additives which are detrimental to health and safety of recycling workers. This shall aid the ability for plastics containing such substances of concern at present, to be recycled once their use has been phased out of the applications that utilize them.

The development of quality standards for recycled plastic material with testing procedures, at a price attainable by SME recycling industries, in order to provide quality assurance to product manufacturers is required. Concurrently an increase, and updated, information flow between the recycling and manufacturing industries should be established.

Common definitions of what constitutes recovery and recycling along with minimum energy recovery efficiency standards are required to create and provide incentives to utilize plastics in the most resource efficient manner and overcome the associated regulatory risk to development. Stringent monitoring and control of waste export consignments is also required to encourage effective separation of waste resources and aid in levelling the playing field between domestic and foreign recyclers with regard to sourcing post use plastic material. The export of post use plastics (and regranulate) does have advantages and disadvantages as discussed in chapter 7. However the risk of markets collapsing is significant and needs to be taken into consideration for long term viability and security of market.

Collection versus Market or Technology developing first

There are two further issues that require to be addressed when developing recycling schemes, it should of course be stressed that when designing a waste management system it is of great importance to focus on the whole chain in order to avoid suboptimal solutions. However the order in which development takes place is important with these two issues in particular often resulting in development dilemmas.

The first of these is the market for recyclate or collection of material. It has been identified that the development and establishment of viable high end markets for recycled plastic materials is one of the main drivers to increasing the volumes of plastics being recycled. However, in order to establish markets and increase the demand for recyclate there must be sufficient volume and quality of post consumer materials collected and available for recycling at reasonable cost. At the same time collection companies are often reluctant to include plastics in collection schemes until viable markets exist. Therefore a catch-22 situation may arise whereby markets are inhibited from developing due to a lack of materials, and collection schemes do not develop due to a lack of market. This is being overcome through political intervention stipulating mandatory material recycling targets which are providing the incentive to develop collection and relying on markets to develop as a result of increased collection. Viable markets do exist for certain polymers and product types both domestically and, abroad. However the pull of materials from Western Europe is having an impact on developing domestic markets as the critical mass of high quality material is not always readily available domestically.

In this situation recyclers often state that there is a lack of materials available at reasonable price along with a lack of markets for certain polymer types being collected. At the same time manufacturers state that there are variable volumes and a lack of high-quality recycled plastics to meet their requirements in order to consider the wider use of recyclate in their products. Technology innovation improving and assuring the quality of resultant material is aiding the wider use recyclate by domestic manufacturers as previously stated with PET food packaging products. However there is still clearly a need for further quality assurance techniques to be developed and producers to actively include recycled materials within their products if markets for collected materials are to be secured thereby enabling further resource savings to be made.

The second is whether technology to treat the post consumer material (where the resultant product has an established market) or the collection of material should be developed first. The RGS90 PVC recycling process is an example of such an issue. In this case the technology maybe available to treat PVC waste and markets for the resultant products exist. However the materials required to feed the process are not available in sufficient quantities to reduce the gate charge to an extent whereby it is competitive with alternatives such as landfilling and incineration thereby making the process more attractive to waste collection firms, local authorities and industry. This has been discussed in section 7.3 with regard to technology, market and regulatory risks associated with technological innovation developments and commercialization which highlights the fact that there are a number of risks related with such developments. In order for these technologies to develop it is clear that they are subject to open market forces and therefore require being cost competitive on the global market for material and alternative treatment options.

However, in order to encourage resource recovery and utilization creating a transition up the waste hierarchy, and reduce some of the risks associated with such developments, further intervention maybe required. Through the use of economic instruments to raise the price of the least desirable alternatives (i.e. landfill and incineration taxes) or mandatory or voluntary material specific collection targets may provide a basis for which to invest and allow for new technologies to become commercialized and obtain the critical mass of feed materials for which to make the process viable. There may initially be a period whereby separately collected materials have no or limited technologies for which to treat them, however, as has been seen with packaging materials, market forces and innovation shall likely fill the gap.

An alternative to directing attention to the waste streams, or in conjunction with such attention, is to support national or regional innovation systems thereby aiding the development of processes capable of treating the wastes arising at a competitive cost. In such a situation whereby technology becomes available at a reasonable price, then materials are more likely to be pulled from the waste streams through market forces alone without the requirement for mandatory material specific collection targets. This may prevent a situation where technology is pushed to develop too rapidly to treat the collected material which may result in sub-optimal treatment processes if material targets are set before viable technologies to treat them are developed.

Recommended Further Research

A number of issues that warrant further research have arisen from this work, the most interesting an important of which are presented forthwith.

Bio-polymers including PLAs and PHAs are beginning to enter the packaging market including beverage bottle and food tray applications in increasing volumes. It is hypothesized (by the author) that schemes such as the PET beverage bottle deposit refund systems, if producers see these as the best means of achieving their producer responsibility targets for reclaiming and recycling their quota of packaging, may inhibit a change from PET to PLA plastic bottles if a clear means of recovering such bio-polymer material from the waste stream to meet their obligations are not developed. Where deposit refund systems are not in operation, and PET bottle collection is carried out through mixed polymer kerb side collection, the lack of automated separation systems may also affect PLA replacing PET as identification and separation of the two polymer types becomes increasingly complicated as volumes of PLA increase. This has important implications on the wider adoption and market establishment of bio-polymers within the soft drinks packaging sector within a number of countries throughout Europe. At the same time however limited studies (i.e. LCA) have been conducted to compare the benefit of PLA bottles over a scheme where PET may be mechanically recycled in a closed loop system up to nine times (such as in Germany, Switzerland and Sweden), or chemical recycled numerous times (such as the process emerging within Italy). Further research into both recycling targets and established schemes for PET collection /recycling and an studies such as an LCA into PET recycling versus PLA collection and end-of-life treatment are interesting areas as bio-plastic volumes increase and conventional polymer collection and recycling schemes become more established.

A further area which has been found to be a key driver to further recycling developments within the plastics sector is innovative technology. Innovation systems have been defined by Lundvall (1992) as "the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge". Johnson and Jacobsson describe five functions that are served within such a system including:

- The creation and diffusion of 'new' knowledge;
- An aid to guide the direction of the search process among users and suppliers of technology;
- Direct and enable the supply of resources including capital, competence and other resources;
- To create positive external economies through the exchange of information, knowledge and vision; and
- Facilitate the formation of markets

Research into national innovation systems for recycling and recovery technologies has not been identified by the author and such work would appear beneficial and interesting so as to determine how such technologies can be promoted and become commercialized within individual member states and the EU as a whole.

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Appendix 1. Organisations and Companies Interviewed

Organisations and companies interviewed in order to determine the general issues, trends, developments, challenges, and drivers relating to the management of End-of Life plastics and products containing plastics are presented. A substantial number of others were contacted, however due to a number of reasons they were unavailable for commenting on this subject.

Type of organisation	**Company and location**
Plastic Packaging waste Producer Responsibility Organisations:	RECOUP – UK Plastretur AS – Norway DSD – Germany Plastkretsen – Sweden
Recycling/ recovery companies:	H. A. Industri A.B. – Sweden Plastic Recycling RLS A.B. – Sweden Mann Organisation – UK Smile Plastics Ltd. – UK Smile Plastics B.V. - Netherlands Linpac – UK Cleanaway Plastic Recycling – Germany RGS90 – Denmark Cynar Plc. – UK & Ireland CK Polymers Ltd – UK
Collection Companies:	Shanks Waste Solutions – UK IL Recycling – Sweden NSR – Sweden
Plastic Processors:	J.Krebs & CO.$^{A}/_{S}$ – Denmark Polimoon Ltd. – UK
Bioplastics:	IBAW (The international industry platform for bio-plastics & biodegradable polymers) – Germany AnoxKaldnes A.B – Sweden
Other organisations:	WRAP – UK Score Environment – UK Environmental Protection Agency – Ireland PlasticsEurope – UK office Aberdeen City Council - UK Ozmotech Pty – Australia

Appendix 2. Introduction to copolymer, blends and composites

To achieve these desirable qualities and remain competitive on the market place various polymer properties beyond that of a single polymer block can be obtained through the synthesis of copolymers or creation of polymer blends. Copolymers are polymers which contain two or more different monomers on the same polymer chain (polymers of single monomer construction are homopolymers). Polymer blends are plastics which contain two or more polymer types. Many polymers are immiscible with other polymer types with the two polymers repelling each other due to the amplified effect of intermolecular forces (amplified due to the length of the polymer chains) on the miscibility of the polymer types causing two separate material phases within the plastic and not a single copolymer structure. In order to create a polymer blend compatibilizers are used which are often in the form of grafted copolymers. An example of where copolymerization can result in beneficial materials is styrene copolymers. Polystyrene its self is a hard yet brittle material however, if combined with a rubber in a copolymer the resulting material is much tougher and therefore has more desirable characteristics for a number of applications. An example of this is in the construction of High Impact Polystyrene (HIPS) which combines a polystyrene and polybutadiene rubber. This fusion has to occur in a polymerization or grafting process where the polybutadiene polymer chains are grafted onto a polystyrene backbone resulting in the two polymers chemically bonding and acting as a compatibilizer. If polybutadiene and polystyrene are merely mixed during fabrication then phase separation occurs due to the intermolecular forces as previously mentioned. Another styrene graft copolymer is the engineering grade copolymer Acrylonitrile Butadiene Styrene (ABS), made through the polymerization of styrene and acrylonitrile monomers to create a copolymer plus the addition of polybutadiene to form a grafted copolymer blend. ABS is utilized in high specification products especially in electrical and electronic casing applications due to strong, rigid, high impact shock absorbance, long life and lightweight properties (EIPPCB, 2005; Goodship, 2001; Athalye, 1995).

Composite materials represent another possibility for creating desirable properties within plastics. Composites combine the properties of two or more materials to enhance the mechanical properties of each to create a new product which has the advantages of each of the component materials. Common plastic composites take advantage of strong fibres such as glass and carbon fibres or natural fibres such as flax, hemp or cellulose combining them within a binding matrix resin such as polyester, polypropylene or epoxy among others. Through the integration of strong fibres within the resin matrix, the resulting material is capable of withstanding much higher degrees of load, tension and shear than any one of the constituent materials alone (Athayle, 1995).

Appendix 3. Total plastics consumption by type, Western Europe, 1996, 2001 – 2003 (x 000 tonnes).

Plastic type	**1996**	**2001**	**2002**	**2003**	**% change ’02 - ‘03**
THERMOPLASTICS					
LDPE/LLDPE	5,553	7,263	7,501	7,577	+1.0
HDPE	3,731	4,907	5,198	5,285	+1.7
PP	4,167	5,567	6,007	6,109	+1.7
PVC	4,906	5,305	5,308	5,382	+1.4
PS/EPS [1]	2,551	3,083	3,118	3,136	+0.6
PET	954	2,134	2,368	2,577	+8.8
ABS/SAN [1]	540	792	788	803	+1.9
PMMA [1]	257	302	317	327	+3.2
Acetals [1]	111	176	181	186	+2.8
Polycarbonates [1]	233	411	446	471	+5.6
Polyamides	1,027	1,305	1,330	1,328	-0.2
Acrylics [2]	0	0	0	0	0
Other [1]	232	530	556	594	+6.8
Total thermoplastics*	**24,262**	**31,775**	**33,118**	**33,775**	**+2.0**
Total including ‘non-plastic’ applications	27,055	36,168	37,576	38,148	+1.5
THERMOSETS					
Alkyd [2]	0	0	0	0	0
Amino	387	869	835	830	-0.6
Phenolics	150	400	386	380	-1.6
Epoxy Resins	55	97	97	98	+1.0
Polyesters	351	405	400	408	+2.0
Polyurethanes	1,293	2,115	2,190	2,235	+2.1
Others	N/A	2,500	2,500	2,500	0
Total thermosets*	**2,236** [3]	**6,386**	**6,408**	**6,451**	**+0.7**
Total including ‘non-plastic’ applications	5,323 [3]	10,519	10,503	10,640	+1.3
Total plastic consumption*	**26,498** [3]	**38,161**	**39,526**	**40,226**	**+1.8**
Total plastic consumption including ‘non-plastic’ applications	**32,378** [3]	**46,687**	**48,079**	**48,788**	**+1.5**

1 = No ‘non-plastic’ applications for this plastic type 2 = No ‘plastic’ application for this plastic type

3 = Data not available for ‘other’ thermoset plastics * = not including ‘non-plastic’ applications

N.B. non-plastic applications refer to products such as textile fibres, coatings, adhesives etc. which are not ‘typical’ plastics applications Source: APME, (2000); Plastics*Europe*, (2004)

Appendix 4. Commercial Biopolymers

Polymer type	Characteristics	Typical and potential applications
Poly-hydroxyalkanotes (PHAs) (Produced by various bacteria by fermentation of carbohydrates under controlled nutritional conditions)	Wet-ability and printability properties similar to thermoplastics such as PET and PP.	biodegradable packaging and moulded goods, non-woven fabrics for flushable wipes and personal care items, films and fibres, adhesives and coatings, binders for metal and ceramic powders, and water-resistant coatings for paper and board.
Polylactic Acid (PLAs) (Produced through polycondensation of natural lactic acid formed through fermentation of carbohydrates)	High gloss and clarity and can compete in certain applications with PS and PET.	Used in rigid packaging for fruits and vegetables, eggs, and bakery products. Films used for sandwich wraps, sweets and flowers. Other applications include stretch blow-moulded bottles for water, juices, dairy products and edible oils. Future applications being researched include automobile components.
Modified starch (Produced from plant starch and water as a plasticizer. plastics can be made out of almost 100% starch or of a mixture of starch with other biodegradable components.)	A number of firms have developed starch based polymers. Several of these materials, besides being biodegradable are water soluble.	The main target market for this application has been as a substitute for expanded polystyrene in food packaging.
Polyester (certain types)	Policaprolactone, synthetic polyester that has costs reportedly marginally superior to those of PET. Other biodegradable and compostable synthetic polyesters have been developed with similar properties to low density polyethylene.	

Sources: Omnexus 2005; Narayan 2004; Bohlmann, 2004

	Fossil energy equivalent requirements in MJ/kg plastic material production		
	process energy (includes fertilizers and transport)	Feedstock energy	Total
Thermoplastic starch pellets	25	0	25
Plastic starch + 15% PVOH	24	6	30
Plastic starch + 50% polyester	32	20	52
PLA (from starch)	53 – 56.7	0	53
PHA (grown in corn plants)	90	0	90
PHA (bacterial fermentation)	80	0	80
HDPE	31	49	80
PET (bottle grade)	38	39	77
PS (general purpose)	39	48	87
PP	43	51	94

Sources: Narayan 2004; Bohlmann, 2004

Appendix 5. Technical limitations to mechanical recycling

In order to protect food products from degrading or spoiling too rapidly food packaging often contains barrier resins incorporated into the packaging material in order to prevent the infiltration of oxygen and water which may accelerate the degradation process of the food product or to prevent aromas entering or exiting the packaging which could spoil the product. Although some plastics utilized in packaging can achieve this without the requirement for an extra barrier layer (e.g. PET and HDPE) and are therefore monolayer structured packaging materials, others require a combination of resins to achieve the desired properties. Some of the most common barrier resins used in packaging today include Polyvinylidene Chloride (PVdC), ethylene vinyl alcohol (EVOH), PET, Polychlorotetrafluoroethylene (PCTFE), nylon, and nitrile copolymers (Graff, 2005). The construction of multilayer plastics packaging typically contains an outer layer of strong, transparent films made of polyesters or PP, while the middle layer contains the barrier resins with the layer coming in contact with the food product often being composed of LDPE. It is the fact that these multilayer packaging materials contain a number of different polymers types which represents another problem in the mechanical recycling process due to limitations of the mechanical recycling process in accepting commingled polymer types to produce a high quality recyclate.

Therefore the most suitable products and commonly collected fraction of the MSW stream to be mechanically recycled are mono-layered plastic bottles made from the crystalline homopolymers PET (e.g. soft drinks bottles) and HDPE (e.g. milk bottles) due to the limited range of polymers and formulations used in these products making separation and single polymer extraction easier. Plastic bottles, however, account for less than 20% by weight on average of the total plastic in municipal solid waste. In past years it has not been generally practical to mechanically recycle the remaining plastics from the domestic waste stream on a large scale, due to the range of polymer types and higher levels of contamination (RECOUP, 2002).

Mixed plastic waste (MPW) can be commingled and mechanically reprocessed as one through the use of compatibilizers, although this produces a lesser quality material than single polymer reprocessing. The resulting material has a mixture of polymers and associated properties which combine without having the complete properties and attributes of any one specific polymer type and due to reasons that shall be discussed the material shall be degraded to a greater extent than if single (homogenous) resin types are mechanically recycled. This presents problems for the end use market of this material. However, although the material is not as valuable as single polymer material it still retains many of the attributes associated with plastics such as rot resistance and versatility, and additional additives can be supplied in order to enhance its resistance to UV degradation, oxidation etc. For these reasons, and due to the lower costs in producing mixed recycled plastic material it has found a number of useful applications in sound barrier construction along side airports and motorways, artificial wood products for example in the construction in garden terracing and fencing as it does not require continual painting or rot when exposed to the elements.

Mixed plastics

As discussed, the fact that in order to achieve a higher quality material, a homogenous polymer type is required as the feed material. Any mixed plastic shall require a compatibilizer so as to create a useful material, all be it a downgraded material. Coloured plastics are also a problem even within the same polymer group (i.e. PET is either transparent or Jazz (coloured)) and when mechanically recycled together produce a grey or off coloured material which has lower attainable market price and demand.

Natural degradation

Plastics naturally degrade during their life span due to exposure to environmental conditions such as Ultra violet light, temperature extremes and react with oxygen in the air. These cause the polymer chains to break down, causing decolouration (i.e. yellowing) of the plastics and reduce the mechanical properties often making the resin more brittle and unusable. This presents a problem as mechanical recycling relies on the mechanical properties of the feed material which is passed through the process to result in the same mechanical properties being exhibited in the recyclate as the mechanical recycling process does not rebuild polymer chains. However additives such as UV stabilizers and anti-oxidants can be added to the resin to prevent this degradation process, however a resin shall only allow a certain amount of additive to dissolve in the material. Over time these additives become inactive due to reactions with air and light, however a benefit of mechanical recycling is that more stabilizer additives can be supplied thereby giving a new lease of life to the material (Jansson, 2005).

Heat and shear degradation

Table 11: Commodity thermoplastics characteristics (Hocking, 1998, p748)

Code symbol	Plastic type/name	Density	Melting point
♳	Polyethylene Terephthalate	1.40	240
♴	High Density Polyethylene	0.94-0.96	130
♵	Polyvinylchloride (PVC)	1.40*	~80
♶	Low Density Polyethylene	0.91-0.93	108
♷	Polypropylene	0.90	176
♸	Polystyrene	1.05#	~100
♹	All other resins	Various	Various

* Un-plasticized. Decreases to 1.30-1.32, depending on formulation used when plasticized.

\# Density indicated for general purpose PS, not expanded PS.

Another limitation that exists with mechanical recycling in terms of closed loop recycling of plastics is the degradation of materials from heat and shearing which occurs each time the plastics material is cycled through the system. As Table 11 above illustrates, different resin types have various and different melting temperatures. If a resin is exposed to temperatures in excess of their melting temperature the material begins to thermally degrade. This presents a particular problem when reprocessing mixed plastic waste due to the temperature for reprocessing having to be as high as that of the resin present in the mix with the highest melting point so as to avoid un-melted granulate entering the product as a non functional and potentially detrimental entity. The resin with the lowest melting point within the mix shall also be exposed to temperatures above its optimum thereby degrading its polymer properties due to the excessive heat breaking down the polymer chain length. This in turn affects the molecular weight of the polymer resulting in deterioration of the mechanical and material functional properties such as strength. This is not only limited to mixed plastics processing however, and over repeated melting and reforming processes polymers degrade where by the polymer chain length, after subjection to repeated heat and shear stress will result in shortening and the molar mass distribution being reduced (It is the average length of the polymer chain within the plastic material and their distribution within the plastic resin that determines the materials molar mass (and not a distinct molecular weight) which in turn is linked to the material's properties) (EIPPCB, 2005). It is therefore generally accepted that in a closed loop recycling system where a 1:1 ratio of a single resin type is utilized to produce the same material (i.e. PET bottle into PET bottle) this process can only occur around 9 times before the mechanical properties are reduced to a point whereby they no longer exhibit the desired properties and are normally only fit for "down-cycling" into a material such textile fibres or strapping tape (Goodship, 2001; Jansson, 2005).

Additives

The widespread use of dyes, fillers, and other additives in plastics also causes a number of difficulties in mechanical recycling. The fillers interfere with the remelt process and distribute unevenly through the resultant material as well as a mix of different additives producing undesirable and variable quality of the regranulate making markets hard to establish due to the inconsistent material produced. The viscous nature of the polymer makes it economically unviable to remove fillers, and the polymer damaged by most processes that could cheaply remove pigments. This is another reason why beverage bottles and plastic film bags are more commonly recycled due to less or no additives being utilized in these products.

Thermoset plastics

Thermoset plastics can not be mechanically recycled as thermoplastics can. This is due to the cross linked polymer structure resulting in a material that is unable to be re-melted and processed in the same way as thermoplastics. This requires the need for efficient separation of polymer types so as thermosets do not enter the thermoplastic recycling system. However thermosets can be processed separately and ground down so as to be used as a filler material within virgin thermoplastic production offering an often economically viable alternative to traditional filler material such as talc and other inorganic fillers.

PVC

PVC has a lower melting temperature (180-210^{o}C) where as other thermoplastics have a typical range of between 220-260^{o}C. If PVC is melt recycled in a mixed polymer stream the PVC thermally degrades prior to the other plastics and goes through dehydrohalogenation, forming hydrochloric acid (HCl) Softened PVC within mixed plastic waste can cause particular problems for mechanical recycling of specific polymer types. When it is remelted along with PET it can cause discolouration of the transparent PET material as well as releasing hydrochloric acid which can not only damage machinery and pose a health threat to workers, it can also severally degrade the PET polymer. Trace amounts of PVC in PET, as low as 100ppm, can cause undesirable qualities of PET which is of particular concern in bottle recycling as softened PVC is often used in bottle caps as a seal and also used as a clear polymer for bottle manufacturing making separation by hand difficult (also separation by density flotation due to the two plastics having similar densities (see table 11). Another problem associated with the mechanical recycling of softened PVC regards the heavy metal additives utilized as stabilizers, upon remelting of the PVC, additives such as Cadmium and Lead can spread throughout the new material, thus contaminating the resulting regranulate or product with unevenly dispersed quantities. This is due to the fact that in comparison to other large-volume thermoplastics (e.g. PE and PP) PVC is a compound material in that it does not consist of polymer alone as it requires stabilizers (to avoid degradation of the PVC), plasticizers (in flexible PVC), fillers, impact modifiers, pigments and processing agents. The varying amounts of fillers, chlorine content, and other additives also makes the recycling of PVC from different production facilities, applications (see table 12) and even production years difficult to produce a high quality recyclate due to the variations in the resultant material based on the feedstock (Plinke, Wenk, Wolff, Castiglione, Palmark, 2000).

Table 12: Typical composition of PVC compounds (Plinke, Wenk, Wolff, Castiglione, Palmark, 2000)

Application		**Share of the components (weight-%)**				
		PVC polymer	**Plasticiser**	**Stabilizer**	**Filler**	**Others**
Rigid PVC applications	Pipes	98	-	1-2	-	-
	Window profiles (lead stabilizers)	85	-	3	4	8
	Other profiles	90	-	3	6	1
	Rigid films	95	-	-	-	5
Flexible PVC applications	Cable insulation	42	23	2	33	-
	Flooring (calender)	42	15	2	41	0
	Flooring (paste, upper layer)	65	32	1	-	2
	Flooring (paste, inside material)	35	25	1	40	-
	Synthetic leather	53	40	1	5	1
	Furniture films	75	10	2	5	8
	Leisure articles	60	30	2	5	3

Other concerns surrounding PVC use is the effects of phthalates which are utilized as a plasticizer (a softening agent) in the manufacturing of softened PVC which is, without the addition of softeners, a hard plastic. Phthalates, which are a group of chemicals produced from phthalic anhydride and alcohols, are added to PVC in order to allow the long polyvinyl molecules to glide over each other thereby creating a soft form of PVC which is flexible and can be formed into a number of different shapes. Major applications of soft PVC include children’s toys, flexible piping (e.g. garden hoses), protective clothing (e.g. rain coats), electrical cabling insulators, shower curtains, and medical products. A number of different phthalates are utilized as softener additives in PVC including di(2-ethylhexyl)phthalate (DEHP) being the most widely used softening agent, followed by lesser quantities of diisononylphthalate (DINP), diisodecylphthalate (DIDP), and butylbenzylphthalate (BBP). Plasticizers in general are not reactive substances and do not chemically bond to the PVC which on the one hand allows the polymer chains to glide over one another, however on the other hand this results in phthalates being released in small quantities through natural evaporation and migration or may be washed out of the PVC products by water.

Appendix 6. Food safety considerations: closed loop food packaging recycling

With the aim to avoid the migration of adventitious substances from packaging to food products, there have been several EU Directives associated amendments adopted, the latest of which being the 2004 Commission Directive 2004/19/EC relating to plastic materials and articles intended to come into contact with foodstuffs. This Directive stipulates requirements and lists which monomers, polymers and additives may be utilized for such purposes so as to avoid any adverse impact on human health from such migration of undesirable substances into the food stuffs (OJ, L71, 2004). With respect to this, there is a requirement for food packaging producers to ensure that their package does not constitute a hazard to health irrespective of whether or not the materials used are from recycled or virgin sources.

Food and beverage producers therefore require having a guarantee that the packaging materials utilized for their products do not contain any substances that may potentially migrate and come into contact with the food product. The risk of such substances occurring within plastic recyclate is fairly high as the mechanical recycling process can not alone remove all non-polymeric materials within the waste feed and, unless separation of the various polymers achieves 100% homogenous material, there is no guarantee that the resin is of one known type (Williamson, pers comm., 2005). This risk is not only present with the recycling of containers as it is also pertinent to the reuse of refillable bottles. Although recyclate has potential to contain many contaminants introduced from a number of materials entering the process, substances relevant to both cases may arise from flavour residing in the plastic resin from the first use, potentially causing an off-odour or an off-taste in the second product. Alternatively it may be as the result of consumer misuse of the bottle whether that be from storing another food product within the bottle or from storing chemicals such as cleaning agents, automotive products, pesticides or other hazardous products, the latter being of greater concern from a health and safety point of view (Widén, Leufvén & Nielsen, 2005). In the case of refillable beverage bottles, the type of beverage to be packaged within such a system is restricted to those which pass a test ensuring that the migration of flavours and odours into the polymer is not such so as not to be removed through the cleaning process. Automated monitoring systems also identify any contaminated bottles and the number of trips the bottle has made in order to remove old or contaminated bottles prior to refilling (Widén *et al.,* 2005). Therefore refillable systems minimise the risk of contaminants entering the foodstuff through migration by setting strict quality control measures from the products that can be packaged, to the pre-filling monitoring stage.

With single use food contact packaging materials there are no restrictions placed on the product contained within (from a packaging perspective not food standards perspective) and therefore more contamination potential exists. Collection within a commingled material system also gives rise to other foreign substances migrating into the polymer. Monitoring and testing of the materials after recycling is therefore essential prior to utilisation as a food contact packaging material where conventional mechanical recycling is used.

Appendix 7. Extended Producer Responsibility

Within the EU and other OECD countries the concept of Extend Producer Responsibility (EPR) is becoming increasingly utilized as an environmental policy approach with both the WEEE and ELV directives stipulating requirements for producers to take responsibility for the end-of-life management of their products.

EPR is an environmental policy approach under which producers are required to accept significant responsibility (financial and/or physical) for the treatment or disposal of post-consumer products, incorporating the Polluter Pays Principle in to the product life cycle by way of encourage the private sector to take a shared responsibility for efforts to reduce the environmental impacts associated with the production, use and disposal of their products (OECD, 2001). Three general effects of an EPR system can be noted including:

1) Internalizes the external cost associated with managing end of life products through a combination of economic and physical responsibilities, thereby shifting the costs of operating waste management systems from the local authority (general tax system) towards the producer;

2) Diversion of waste from landfill and other direct disposal routes and increasing sustainable resource use through the reuse and recycling of goods and materials; and

3) Encouraging design for the environment of products thereby reducing resource consumption (e.g. materials and energy) and waste production, and aiming to eliminate hazardous waste generation (including the associated environmental burden both upstream and downstream of their position on the supply chain) (ECOLAS – PIRA, 2005).

Several policy measures and instruments have been employed for implementing EPR systems for various products and waste streams which can be split into three main categories (OECD, 2001):

- Product take-back, (voluntary or mandatory approach) which require producers to take-back products (e.g. packaging) after consumer use. This is often associated with set targets for collection, recycling/reuse which the producer takes responsibility for meeting.

- Economic instruments, including such systems as: Deposit/refund schemes, where the deposit on the product acts as an incentive for the consumer to return it to the producer in return for the initial deposit paid; Advanced disposal fees, where by a fee is levied on the product at point of sale to cover waste management costs and producers are responsible for the physical collection and or treatment of the product post use; and Material taxes, such as a tax applied to certain (e.g. hazardous) materials so as to reduce their use and promote ecological favourable alternatives, the tax being utilized for collection and treatment of these materials with the physical responsibility allocated to the producer or financed by them.

- Standards, including minimum recycled content being utilized within products so as to encourage the take back and in turn recycling and reuse of products or materials.

The responsibility can be undertaken by individual producers or, especially where the product is widely distributed throughout a large region and number of consumers, a collective responsibility maybe applied. In such cases a Producer Responsibility Organisation may be created which collects fees from producers in proportion to their product market share and take on the coordination and financing of the physical responsibility required thereafter to ensure the responsibility is being met (ECOLAS – PIRA, 2005).

Appendix 8. Plastics waste and product type collection schemes and obligations

Waste stream	**Material/product**	**Collection scheme**	**Reclamation obligation**
Packaging waste (Industrial, commercial and municipal)	PET bottles (natural & coloured)	• Targeted collection/ drop off points • Voluntary bring system • Deposit/refund system • Kerbside collection • Commingled MSW collection scheme	Packaging and packaging waste directive (most national procedures and legislations have adopted producer responsibility obligations)
	HDPE bottles; PP trays and other dense plastics; LDPE films and other soft plastics; Other plastic packaging	• Kerb side collection • Voluntary bring system • Contracted collection from commercial and industry facilities • Commingled in MSW collection scheme	
Municipal plastics (Non-packaging limited complexity goods)	Various polymer types. Includes sledges, garden furniture, children's toys, kitchen utensils etc	No specific collection. Mainly commingled in general MSW collection system. Separate collections carried out on a limited basis on voluntary bring system and kerb side collections.	No set obligation or target
Non-municipal waste	Industrial processing scrap (Various polymer type)	In-house re-processed or contracted collection between collection companies and/or recyclers and individual facilities	No set obligation or target
	Agricultural film	Contracted collection between collection companies and/or recyclers and individual farms or commingled with other wastes	No EU wide obligation. National commitments in place in Norway, Netherlands, Ireland and Spain
	Building and construction waste	Commingled with other wastes. Carried out on an Ad hoc basis between demolition companies, collection companies and recyclers.	No EU wide obligation. PVC commitments in certain countries.
Complex products containing plastics	Electrical and Electronic Equipment	• Drop off/ bring centres • Return to store • Contracted collection • Commingled with other wastes.	Reclamation and producer responsibility obligation with product specific recycling targets set under WEEE directive
	Vehicle/ automobiles	Take back system run by car manufacturers, importers and retailers. Drop off at authorised treatment facilities.	Reclamation and producer responsibility obligation with product specific recycling targets set under ELV directive