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MASTERARBEIT

Recycling and Energy Recovery of Plastics in Commercial and Industrial Waste: An Analysis of the Situation in the UK and Austria

von
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VORWORT

Die vorliegende Masterarbeit entstand im Zeitraum von Mai bis Oktober 2010. Da es sich um eine vergleichende Analyse der Verwertungsmöglichkeiten von Kunststoffabfällen zwischen Großbritannien und Österreich handelt, wurde die Arbeit in beiden Ländern ausgearbeitet und verfasst. In Großbritannien wurden in Zusammenarbeit mit dem Abfallunternehmen Shanks – Waste Solutions, welchem ich meinen Dank für den Zugang zu den Abfallsortieranlagen ausspreche, Daten zu Kunststoffabfallaufkommen erhoben und chemische Analysen verschiedener Kunststofftypen durchgeführt. Diese primären Daten wurden mit österreichischen, sekundären Daten verglichen um die vergleichenden Berechnungen durchzuführen.

Mein besonderer Dank gilt meinen Betreuern Herrn Prof. Stefan Petrus Salhofer vom Institut für Abfallwirtschaft, Universität für Bodenkultur Wien und Herrn Prof. Simon Collinson sowie Dr. Stuart Wagland von der Cranfield University.

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Elisabeth Leiter

ZUSAMMENFASSUNG

Trotz des doppelt so hohen Aufkommens von Industrie- und Gewerbeabfall (I&G) im Vergleich zu Hausmüll, ist das Wissen über I&G-Abfall gering und die Datenlage schlecht. Die Sammlung und Verwertung von I&G-Abfall unterliegt nicht derart strikten Regelungen wie jene von Hausmüll, mit der Folge, dass eine erhebliche Menge I&G-Abfall noch immer auf der Deponie endgelagert wird.

Das Verwertungspotential von I&G-Abfall wird als hoch eingeschätzt und wird von dieser Studie für Großbritannien und Österreich analysiert. Daten über Aufkommen, Sammlung und Verwertung von I&G-Abfall mit besonderer Hervorhebung von Kunststoffabfall werden miteinander verglichen. Zudem wird berechnet, ob Recycling oder die thermische Verwertung von Kunststoffabfall aus ökonomischer Sicht günstiger ist.

Chemische Analysen von handsortierten Kunststofftypen ergaben einen hohen Heizwert von ca. 30 kJ/kg. Dieser Wert ist mit jenem von Kohle vergleichbar wodurch die thermische Verwertung sehr attraktiv scheint. Ökonomische Berechnungen zeigten, dass die thermische Verwertung in einem Kraft-Wärme-Kopplung Kraftwerk, verglichen mit Recycling, ökonomisch attraktiver ist. HDPE ist allerdings in beiden Ländern ökonomischer, wenn es dem Recycling zugeführt wird, PET clear in Österreich und LDPE in Großbritannien. Wird Recycling dagegen mit der thermischen Verwertung in einem Elektrizitätskraftwerk verglichen, so stellt Recycling eindeutig die ökonomischere Variante dar.

Der Wert von recyceltem Kunststoff ist sehr stark vom Ölpreis und dem Bedarf nach Sekundärkunststoffen am Markt abhängig. Beide Faktoren werden in Zukunft vermutlich steigen, wodurch sich der Marktwert von recyceltem Kunststoff erhöht und somit die Wirtschaftlichkeit von Recycling als Verwertungsoption.

ABSTRACT

The understanding of commercial and industrial (C&I) waste is comparatively limited, despite an annual arising of more than twice as much as municipal solid waste (MSW). C&I waste data are rarely available and waste from commerce and industries is not subject to such stringent and comprehensive policy targets as MSW, leading to a relatively low recycling rate and to a high amount of C&I waste ending up in landfill. The potential of C&I waste to be recycled or recovered is assumed to be high. The study investigates this potential in the UK and Austria and compares data about arising, collection and treatment of C&I waste with special focus on the plastic fraction. Furthermore, it assesses whether recycling or energy recovery of the plastic fraction of C&I waste is economically better.

Chemical testing of hand-sorted plastic waste revealed a calorific value of around 30 kJ/kg among all plastic types, which is comparable to that of coke and certainly very high if compared to other waste materials, making the energy recovery option quite attractive. It was found that at present, in the UK and Austria, energy recovery in a combined heat and power plant represents the economically favourable option if compared to recycling for all plastic types except HDPE in both countries, PET clear in Austria and LDPE in the UK. However, if energy recovery in an energy from waste plant with electricity usage only is assumed, recycling performs significantly better in terms of the economics.

The value of recycled plastic depends strongly on the oil price and the market availability, both of which are supposed to increase in the future leading to a higher value of recovered plastic and increasing the attractiveness of the recycling option.

ABBREVIATIONS

ATT	Advanced Thermal Treatment
C&I	Commercial and Industrial
CHP	Combined Heat and Power
CV	Calorific Value
Defra	Department of Environment, Food and Rural Affairs
EA	Environment Agency
EfW	Energy from Waste
HCl	Hydrochloric acid
HDPE	High density polyethylene
HHV	Higher heating value
KW	Kilowatt
LCA	Life Cycle Analysis
LDPE	Low density polyethylene
LHV	Lower heating value
MJ	Megajoule
MRF	Material Recycling Facility
MW	Molecular Weight
MSW	Municipal Solid Waste
NIR	Near Infra Red
PET	Polyethylen terephthalat
PP	Polypropylene
PS	Polystyrene
PSW	Plastic Solid Waste
PU	Polyurethane
PVC	Polyvinyl chloride
VM	Volatile Matter
WEEE	Waste Electrical and Electronic Equipment
WID	Waste Incineration Directive
WRAP	Waste and Resources Action Programme

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1 Introduction

In 2004 the United Kingdom produced about 335 million tonnes of waste, corresponding to 5.6 tonnes per capita. Mining and quarrying as well as construction and demolition represent the biggest proportion, both contributing to the total waste arising at about 30%. These are followed by commercial and industrial (C&I) waste accounting for 25% which corresponds to about 83 million tonnes. Household waste represents a relatively small proportion with only about 30 million tonnes (Defra, 2006a).

In Austria, 56.34 million tonnes of waste have been produced in 2008, which corresponds to 6.8 tonnes per capita (BMLFUW, 2009). Almost half of the total is represented by mining and quarrying while construction waste accounts only for 12%. Secondary materials from C&I waste account for 4% of the total. However, since this data represents only the separately collected waste fractions, a certain amount of C&I waste is recorded within other waste fractions, like waste form households and similar facilities or other wastes (BMLFUW, 2009).

Despite the significance of C&I waste in amount and composition, it is not subject to the same stringent and comprehensive targets and policies as the ones for municipal solid waste (MSW). Consequently, in the UK, the recycling rate of C&I waste excluding process scrap is inherently lower and much of the waste from the commerce and from industries still ends up in landfills (Letsrecycle, 2010a). Landfill does not represent a sustainable disposal method due to the wasting of potential resources and the emission of greenhouse gases and other harmful substances into air, water and soil. Additionally, landfill will become less and less economical due to the yearly landfill tax increase of £8/tonne/year until 2013 corresponding to a landfill tax amount of £72 by April 2013 in the UK (Morrison, 2009). Furthermore, the European landfill directive regulates that only pre-treated waste and no biodegradable waste can be landfilled and the accepted waste is restricted to a total organic carbon (TOC) content of less than 6% (Morrison, 2009). Finally, a European law bans the disposal of recyclable materials in landfills by the year 2025 (Dalgleish, 2009).

The today's consumer society is producing commodities and discarding them after fulfilling their functionality at an unsustainable rate. Since this trend is not supposed to change in the future it will entail increased arising of both MSW and C&I waste (Al-Salem et.al., 2009). In order to supply the demand for the people's high-standard living and to do business in a sustainable way, resource efficiency through reuse, remanufacturing, recycling and energy recovery of waste materials are inevitable waste management measures (Patel et.al., 1999).

Strategies have recently been introduced to address not only MSW but also C&I waste assisting the producers of goods to divert the amount of waste from landfill (Defra, 2007). Industries are encouraged to treat their waste in a sustainable manner by using natural resources more efficiently, by recycling and by recovering energy from the remaining waste. Moving C&I waste away from landfill not only provides resource efficiency and environmental benefits, it also leads to economic advantages for business.

Depending on the waste material, the economically optimised recovery option might differ. While in the case of aluminium or glass the benefits of recycling are obvious, the recovery option of plastic waste might alternate between recycling and energy recovery depending on various factors such as waste contamination, separation facilities, market availability (Lea, 1996). Focusing on the plastic proportion of C&I waste, this study assesses recycling and energy recovery treatments and compares them in terms of their economical performance for both, the UK and Austria.

The **specific aims** of the study are listed below:

- Investigation of plastic arising in C&I waste based on the literature and on waste sites in the UK.
- Identification of different plastic types by sorting them out manually on the waste sorting sites and assessment of the availability for recycling.
- Testing of the chemical composition of the different hand-sorted plastic types for identification of the energy recovery potential.
- Identification of existing and emerging recycling and energy recovery technologies as well as markets for recycled plastics in UK and Austria.

- Determination of the economically better option by comparing the value of recycled plastic with the energy value and assessment of the sensitivity of the analysis to potential future changes in energy prices and commodity values.

The economically better option between recycling and energy recovery will be determined for both, the UK and Austria by taking into account the country-specific recycling and energy recovery values and prices, the C&I waste composition as well as the availability for recycling the plastic fraction.

2 Literature review

2.1 C&I waste arising and management

2.1.1 C&I waste arising and composition in UK

C&I waste is composed of waste by the commerce (retailers and wholesalers, public sector, shops, offices and catering establishments) as well as by industries (factories, manufacturers, chemical and other industrial plants) (Defra, 2007).

In the UK, C&I waste arising, as compared to MSW, are not recorded by the Local Authorities as a separate waste stream since they are usually mixed with further wastes, for example from households, once the waste has been collected from the C&I premises. Often, C&I waste is not segregated at source, resulting in a mixed waste of cardboard, plastic, glass etc. and businesses are not obligated to report their waste generation. The missing regulation of C&I waste collection makes it difficult to impose a comprehensive management scheme for C&I waste (Morrison, 2009). Councils do not regulate the amount of recycled plastic from C&I waste and the amount of recyclable material present in the residual C&I waste stream is high. However, Dalgleish (2009) states that the amount of C&I waste sent to landfill will be legally restricted to 20% against the levels of 2004 and by 2025, based on a European ban, no recyclable material can be disposed of in landfills anymore.

Since in Austria the C&I waste is recorded within different waste categories which comprise wastes from different origins, its total arising is also difficult to measure (BMLFUW, 2009).

The Environment Agency (EA) of England and Wales carried out a study to record the C&I waste amount in England only and identified that in 2002/3 about 68 million tonnes of C&I waste was produced, accounting for more than twice as much as household waste, the latter representing 25 million tonnes (Defra, 2009). Roughly one quarter of the total waste arisings in England is generated by commerce and industries, whereas households produce only 9% (Defra, 2006b).

The 68 million tonnes of C&I waste are split into 30 million tonnes from the commerce and 38 million tonnes from the industries (Defra, 2006b). This distribution is illustrated in Figure 1, which also shows the C&I waste arise by industry sectors adopted from the Standard Industry Classification codes (Greifenberg *et.al.,* 2008). The dotted fractions represent commercial, whereas the plane fractions represent industrial sectors. Future forecasting indicates that C&I waste will increase significantly until 2020. This rise, however, will be driven more and more by the commercial rather then by the industrial sector due to an increased service sector employment along with a decline in industries (Defra, 2007).

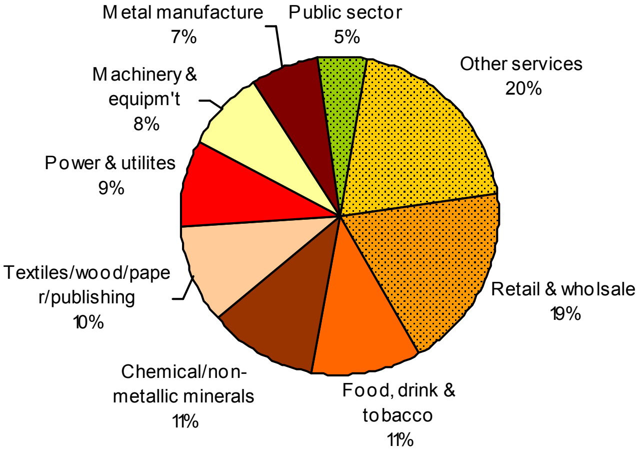

Figure 1: C&I waste arising by sector
(Defra, 2006b)

Regarding the types of C&I waste, which are defined by the Substance Orientated Classification adopted from the Eurostat codes, there is no waste stream dedicated exclusively to plastic, partly due to the lacking segregation at source. Figure 2 shows the streams of C&I waste and its proportion, based on the data from the 2002/03 survey (Defra, 2009). A recent study carried out by Urban Mines for Wales (Scholes *et.al.*, 2009) shows a clear concordance with the data from the EA-survey in 2002/03 in terms of C&I waste streams. Within these waste streams, two are composed of a certain percentages of plastic. The first one is classified as ‘mixed waste’ which accounts for 32% of the total and according to Dalgleish (2009), about 20% of this stream is composed of plastics. The second one is classified as ‘chemical / non-metallic minerals’ which accounts for 20% of the total C&I waste (Dalgleish, 2009).

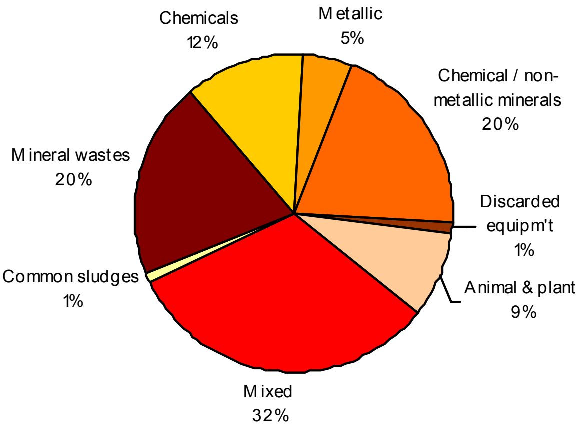

Figure 2: C&I waste types

(Defra, 2006c)

The fraction of the ‘mixed waste’, representing literally the residual waste stream is primarily subject to this study as it was examined at the waste sites. Table 1 shows the composition of this fraction.

Component material	**%**
Cardboard	20.85
Recyclable paper	20.64
Kitchen non compostable	12.90
Plastic film	**10.33**
Rigid plastics	**8.96**
Glass	7.35
Ferrous metals	5.81
Others	4.18
Kitchen compostable	3.97
Wood	2.25
WEEE	1.62
Compostable paper	0.61
Non recyclable paper	0.52
TOTAL	**100**

Table 1: Waste composition of mixed C&I waste

(Dalgleish, 2009)

From the total of 83 million tonnes of C&I waste produced in the UK about 26.5 million tonnes are 'mixed waste' (32%) and according to the composition in Table 1, the plastic waste from C&I sectors represents 5.3 million tonnes. To this amount a certain amount of plastics derived from the 'chemical / non-metallic minerals' has to be added. However, according to Dalgleish (2009) this proportion is supposed to be relatively marginal.

This figure does not exactly correspond to the data estimated by Defra which claim that 3.3 million tonnes of plastic are generated by the C&I sectors in the UK annually (Defra, 2007). Out of the 3.3 million tonnes 2.5 derive from commerce and 0.8 from industries. The total amount of plastic waste is estimated to account for 5.9 million tonnes; thus more than half of the total amount of plastic waste is generated by the commerce and industries. The distribution between film plastic and dense plastic is equated to 3.1 million tonnes being plastic film and 2.8 million tonnes being dense plastic. Furthermore, according to Shonfield (2008), the plastic consumption in the UK will increase by 2% to 5% annually over the next few years.

Figure 3 shows in which Standard Industrial Classification (SIC) sectors the most plastic is generated. It appears that more than half of the plastic waste is produced by the commerce, most of it in the public sector accounting for 21% followed by other services with 18% and retail and wholesale with 17% (Dalgleish, 2009). However, it has to be kept in mind that this data originate from a C&I survey conducted in London and might appear slightly different in more rural areas.

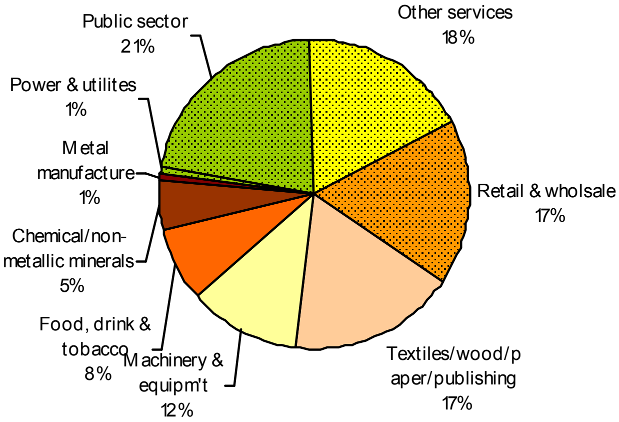

Figure 3: Plastic waste generation by sectors
(modified from Dalgleish, 2009)

2.1.2 C&I waste arising and composition in Austria

According to BMLFUW (2009), 2.05 million tonnes of C&I waste have been produced in Austria in 2008. However, this amount only includes segragated secondary waste materials from commerces and industries without considering other unseparated C&I waste. The waste of electric and electronic equipment (WEEE) from commerce and industries is recorded within the category “WEEE waste” and accounts for 8,140 tonnes. Other C&I waste is recorded within different waste categories like “other wastes”, which besides of commercial waste also considers waste of mineral origin, hazardous waste, other rigid municipal waste and plastic waste and accounts for 8 million tonnes. The category “waste from households and similar facilities” also includes C&I waste from administration facilites, public administration, schools, agriculture, and other facilities (BMLFUW, 2006) and accounts for 3.8 million tonnes. The separate recorded kitchen waste (103,500 tonnes) and food and drink waste (267,000 tonnes) also is composed of a certain amount of C&I waste. Therefore, the arising of C&I waste in Austria certainly is higher than the separatel recorderd 2.05 million tonnes (BMLFUW, 2009). However, due to the imprecise specification about the origin of the waste types within the mentioned waste categories, an exact determination of the C&I waste arising is not possible. By considering the separately recorded C&I waste, only 3.6% of the total Austrian waste arising, is composed of C&I waste. In reality this percentage certainly is higher.

The recorded materials from C&I waste are divided into different waste types defined by the ÖNORM S 2100 and are shown in Figure 4.

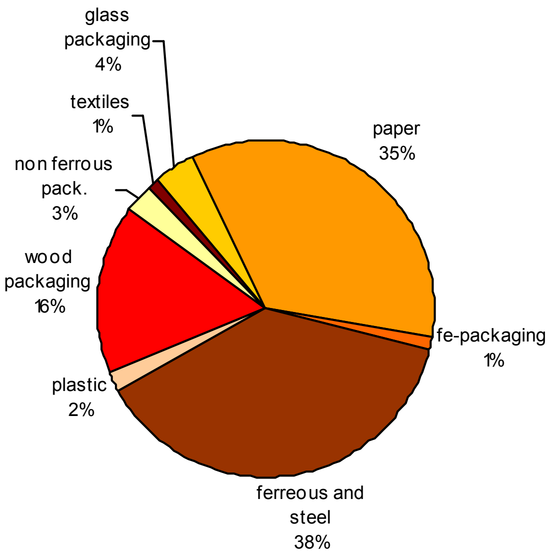

Figure 4: C&I waste types of segregated material only in Austria
(BMLFUW, 2009)

This composition, however, can not be compared to the C&I waste composition of the UK due to the categorisation of other waste types. Many waste fractions which are recorded as C&I waste in the UK, are recorded within other waste categories in Austria. Animal wastes, chemicals, mineral waste and mixed wastes including organics, glass, WEEE, plastics etc., for example, are not recorded within the C&I waste fraction in Austria (BMLFUW, 2009).

As illustrated in Figure 4, plastic waste appears in a proportion of 2% of the total C&I waste, corresponding to 36,100 tonnes. However, there is more plastic waste generated by the commerce and industries which is recorded within other waste categories.
8,140 tonnes of C&I waste is recorded within the "WEEE" category and about 25% of WEEE-waste is composed of plastic. Therefore, additional 2,035 tonnes of C&I plastic waste are produced (BMLFUW, 2009).
Furthermore, within the category "waste from households and similar facilities" there is a plastic proportion of 11%, corresponding to 379,000 tonnes. By assuming that more than half of the plastic is generated by the commerce and industries, as it is the case in England (Defra, 2009), about 200.000 tonnes within this category are C&I waste. Together with the separately recorded C&I plastic waste, this results in about 240,000 tonnes of plastic waste.

It also has to be noticed that within the waste category “other wastes”, there is a plastic waste arising of 522,000 tonnes, without specifying the origin, though (BMLFUW, 2009). Since the plastic proportion within this category is very high, it would be interesting to know how much of this amount derives from the commerce and industries. By assuming that 200,000 tonnes out of 522,000 tonnes is composed of C&I plastic waste, a total of 440,000 tonnes of plastic waste would originate from commerce and industries, corresponding to 0.8% of the total waste arising in Austria in 2008. In the UK, about 1% of the total waste arising is composed of C&I plastic waste.

2.1.3 Waste management of C&I waste in UK

The Environment Agency survey in 2002/03 revealed that 33% of C&I waste was recycled, 9% was re-used, 4% was thermally treated and 41% was sent to landfill (Defra, 2007). More recent studies carried out by Urban Mines suggest that the amount sent to landfill has fallen, while more waste has been recycled (Greifenberg *et.al*., 2008, Scholes *et.al*., 2009). In the North West of England, 47% of total C&I waste arisings was recycled in 2006. However, from the 29% sent to landfill a significant fraction was composed of ‘mixed waste’ containing a considerable plastic proportion (Environment Agency, 2010).

According to Scholes *et.al.* (2009), 70% of the ‘mixed waste’ is possibly recyclable if an accurate segregation at source and market development for the recyclate is in place. Also within the ‘non-metallic wastes’, 88% would be recoverable. As discussed above, these are the waste streams containing a high amount of plastic.

In terms of the recycling and recovery rates by industry and commerce sectors, there is a strong consistency among C&I waste surveys, stating that the recycling performance is well developed amongst industrial sectors, whereas the public sector is recycling only very few materials. The process scrap which is generated in material forming and fabricating industries can be easily recycled or recovered, as revealed by Porter and Roberts (1985). The Environment Agency (2009) states, that 95% of plastic solid waste arising from process scrap was recycled in 2007. Table 2 shows recycling rates of some significant sectors.

Commerce or industry sector	**Recycling rate in %**
Machinery & equipment	60
Metal manufacturing	51
Wholesale and retail	53
Other services	45
Public sector	5

Table 2: Recycling rate of industrial and commercial sectors in 2006

(Environment Agency, 2010)

By assessing the current recycling rate of plastics in C&I waste, two major statements can be made. Firstly, the plastic containing streams ‘mixed waste’ and ‘non-metallic waste’ are generally not handled in a sustainable manner as most of it ends up in landfills and a big proportion would be recoverable or recyclable. A better usage of these waste fractions could be achieved by a better segregation at source. Secondly, the sector with the highest plastic generation has the poorest recycling performance. Hence there is a great potential for C&I plastic waste to be recycled or recovered.

2.1.4 Waste management of C&I waste in Austria

C&I waste materials are utilised as much as possible internally in industries, factories and the commerce. They might be applied in the form of re-use, as secondary material in the form of recycling or as energy source in the form of thermal treatment. If no internal treatment is possible, C&I waste usually is collected separately via transfer- and recycling facilities for C&I waste or directly at the business locations if a certain waste amount arises. Due to a separate segregation at the source there is no need for a sophisticated sorting in the treatment facilities (BMLFUW, 2009).

97% of the separately collected C&I waste has been recycled or thermally treated in 2008 (BMLFUW, 2009).

In order to exploit the minimisation potential of C&I waste, different sector-specific concepts have been developed in order to minimise the not separately collected waste fractions, to increase the quality of the separated secondary fractions and to reduce the risk potential. According to the Austrian waste management law, factories with a certain waste arising and more than 20 employees have to implement a waste management concept and factories with more than 100 employees have to commission a waste management agent involved with the minimisation, treatment and disposal of waste (BMLFUW, 2009).

In Austria, a big minimisation potential for C&I waste is considered to be in the transport packaging via standardisation of reusable packaging (BMLFUW, 2009).

With regard to plastic waste, the minimisation potential is limited due to the advantageous characteristics of the material. However, PVC is supposed to be replaced in future. General plastic waste minimisation can eventually be achieved through integrated waste minimisation strategies. These include intelligent mass-reduction in plastic elements without loosing their mechanic strength and resistance, constructions which are easy to maintain and dismount and adequate material choice in terms of the long-life cycle of the product (BMLFUW, 2009).

The 36,100 tonnes of C&I plastics are collected separately at the location of arising according to the different plastic types PE (HDPE, LDPE), PET, PS, PP and are composed of the fractions foils, bottles, cups, buckets, etc. These waste fractions are mainly recycled and remanufactured to packaging material (foils and containers), constructional elements, garden furniture and electric- and automotive equipment. Only a small percentage of the separately collected C&I materials is treated thermally (BMLFUW, 2009).

By comparing the management of C&I waste in Austria with the UK management system, it can be pointed out that in Austria segregation of C&I waste at source is more common leading to a higher recycling rate of different waste fractions like paper, metals, single plastic types, etc. and a smaller amount of unseparated, mixed waste.

Since 2009 no pre-treated plastic waste has been disposed of in landfills in Austria; they were either recycled or recovered thermally (BMLFUW, 2009).

However, as stated in chapter 2.1.2, C&I waste is also recorded within the waste categories "waste from households and similar facilities". The exact amount of C&I waste within this category is unknown as it is the proportion between separately segregated waste and mixed waste of commerce and industries. The treatment systems of the waste of this category which derives from households, commerce, industries, public administration, schools, hospitals, agriculture and markets, is listed in Table 3.

Treatment method	**In tonnes**	**In percentage**
Biotechnical treatment of organic waste from the separate collection	687,100	18.2
Recycling of secondary material from the separate collection and of sorted material from the mechanical treatment	1,227,500	32.2
Treatment of hazardous WEEE material from the separate collection	88,500	2.3
Thermal treatment of MSW, bulky waste, sorted waste from mechanical treatment with a high heating value and secondary material with a high heating value and or organic material sorted for thermal treatment	1,315,900	34.7
Biotechnical treatment of the organic fraction from the mechanical treatment	329,100	8.8
Untreated waste to landfill: MSW, bulky waste and untreated residues from the sorting of secondary material	138,300	3.7

Table 3: Treatment methods of "waste from households and similar facilities" in Austria in 2008 *(BMLFUW, 2009)*

The untreated waste sent to landfills (last row of Table 3), has decreased from year to year since the Austrian landfill directive (Deponieverordnung) entered into force in 1996.

In Austria, the segregated collection of waste from households, commerce and industries as well as agriculture accounts for almost 60% and is subject to a separate treatment method such as recycling and biotechnical treatment. From the unseparated mixed waste, 42% is subject to a mechanical biological treatment (MBT) and the rest is directly sent to a thermal treatment plant. From the waste treated by the MBT, 58% is then sent to a biotechnical treatment while the rest is treated thermally (BMLFUW, 2009). These data apply to C&I waste excluding source segregated secondary material.

By comparing these data to the UK C&I waste management, the Austrian waste management system is more sustainable due to its high recycling and thermal treatment rates and its landfill disposal rate of only 16%, one fifth of it disposed of directly. In UK, on the contrary, 41% of all C&I waste still ends up in landfill, 33% is recycled, 9% re-used and only 4% is treated thermally (Defra, 2007).

2.2 Definition of Plastics / Polymers

The major issue and concern regarding the plastic waste fraction is its heterogeneity. Over 60 types of plastic polymers exist and are used in numerous applications. Table 4 gives an overview of the main plastic types and its typical use by dividing the types into the two main groups thermoplastics and thermosets.

	Type	**Plastic type mark**	**Use**	**General properties**
Thermoplastics	PET	♳ PET	Bottles, carpets, food packaging	Clear, hard, tough, solvent resistant, high heat resistance
	HDPE	♴ HDPE	Bottles for detergents, housewares, grocery bags, flower pots, pipes, toys, industrial wrapping	Excellent moisture barrier properties, excellent chemical resistence, hard to semi-flexible, strong, soft waxy surface
	PVC	♵ PVC	Pipes, window frames, flooring, wire coating, floor coverings, medical tubing	Excellent transparency, hard, rigid, good chemical resistance, long term stability, good weathering ability
	LDPE	♶ LDPE	Cling-film, refuse sacks, flexible containers, bubble wrap	Tough, flexible, waxy surface, soft – scratches easily, good transparency, low melting point
	PP	♷ PP	Auto motive parts, fibres, containers, pipes, electrical components, bottle tops, lunch boxes	Excellent chemical resistence, high melting point, hard but flexible, waxy surface, strong
	PS (HIPS)	♸ PS	Disposable cutlery, video cases, toys, fast food trays	Clear to opaque, glassy surface, rigid, hard, brittle, affected by fats and solvents.
	Other	♹ OTHER	Various uses (commodity and industry plastics)	e.g. Polycarbonate: easily moulded, temperature and impact resistance, optical properties
Thermo set	PU		Coatings, finishes, mattresses, vehicle seating	
	Phenolic		Ovens, automotive parts	

Table 4: Major plastic types and application

(Michaud et.al., 2010; Aguado and Serrano., 1999 and Achialias et.al., 2007)

Thermoplastics are characterised by a softening point when heated to a particular temperature because of their weak intermolecular forces between the polymeric chains. This feature enables thermoplastics to be reprocessed more than once and to be recycled many times.

Thermosets are cured during processing forming covalent bonds between polymeric chains and hence they cannot be reprocessed or remoulded by heating once shaped into a specific mould (Michaud *et.al.,* 2010). Thermoplastics account for roughly 80 % of the total plastic consumption. LDPE, HDPE and PP represent more than half of all thermoplastics (Al-Salem *et.al.,* 2009).

2.3 Plastic recycling processes

Recycling enables plastic wastes to be reintroduces into the cycle of consumption and it is the only treatment option of waste permitting conservation of raw materials, if compared with incineration and landfill. However, recycling should not be applied if the energy used during the recycling process is higher than the energy necessary to produce new materials (Aguado and Serrano, 1999). Plastic waste can be treated either via mechanical or via feedstock recycling.

2.3.1 Mechanical and feedstock recycling

Mechanical recycling is a method by which plastic wastes are reprocessed for the re-use in plastic products, which might be the same as the source product or a new one. However, the basic chemical structure of the material is not changed (Dodbiba *et.al.*, 2008). Mechanical plastic recycling involves several operational steps starting from the separation of the plastic waste by polymer type and/or colour, which can occur manually or automatically (Aznar *et.al.*, 2006). A separation of clear and coloured plastic is necessary due to their different recycling behaviour when processed. When coloured plastic is melted, the colour becomes grey and therefore it is applied in products like pipes and strapping. Clear or natural polymers on the contrary, can be recycled into food packaging and manufactured into thermoformed products such as cups and trays (Shonfield, 2008). After removing the dirt and contaminants, the plastic can either be melted down directly and remoulded, or shredded and processed into granules. These granulates can then be extruded by heat and reprocessed into new plastic goods (Waste Online, 2006). Figure 5 illustrates the typical steps of a mechanical recycling process.

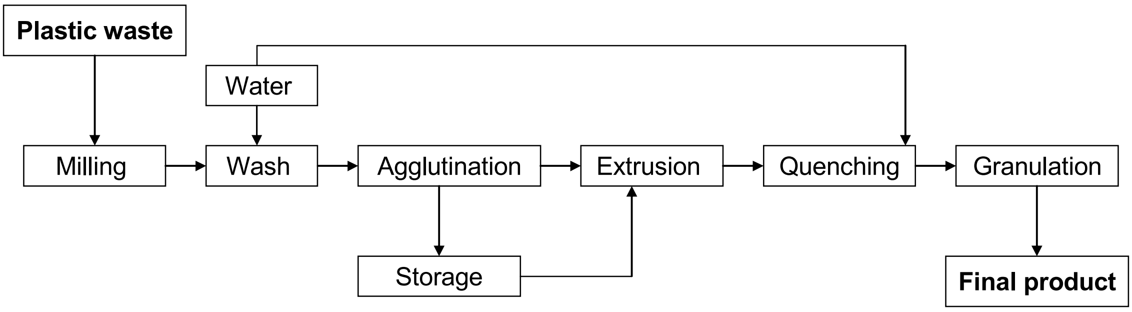

Figure 5: Mechanical recycling steps
(Aznar et.al., 2006)

The moulding process of recycled resin can be conducted via injection, compression, extrusion, blowing or rotation, depending on the type and form of plastic. While injection moulding can be applied to all thermoplastics in the form of granules, compression moulding is applicable mainly to thermosets in the form of pellets or sheets (Morrison, 2009). According to Al-Salem *et.al.* (2009), typical products containing recycled resins are grocery bags, window and door profiles, blinds, pipes, etc.

Feedstock recycling is a recycling process where the plastics are converted into smaller molecules, either by depolymerisation to monomers or by partial degradation into other secondary valuable materials or chemicals (Achilias *et.al.*, 2007). These products, usually liquids or gases, can be used as a transportation fuel or as a feedstock for the production of new petrochemicals or plastics. Feedstock or chemical recycling can be divided into liquid-gas hydrogenation, steam or catalytic cracking as well as glycolysis and hydrolysis. Polymers such as nylon 6 and nylon 66 but also PET can be efficiently polymerised and are advantageous for chemical recycling treatments (Al-Salem *et.al.*, 2009). According to Waste Online (2006), feedstock recycling is associated with very high capital costs and to be economically viable very large quantities of plastic waste are necessary for reprocessing. Therefore recycling of plastic is dominated by mechanical recycling and only a few commercial feedstock recycling techniques exist currently. For this reason, feedstock recycling is not analysed in the present study. Advanced thermal treatments such as pyrolysis and gasification are also often classified as feedstock recycling (Al-Salem *et.al.*, 2009). However, since the main usage of the products generated by feedstock recycling is in the field of energy recovery, the plastic reprocessing techniques pyrolysis and gasification, which are examined in this study, are classified as energy recovery options.

2.3.2 Operational issues and restrictions

The recycling of plastic waste is not as established as the recycling of other waste materials such as paper, glass or metals. This is due to the more complex and heterogeneous physical and chemical properties of plastics, which make the establishment of a general recycling procedure very difficult. (Al-Salem et.al., 2009).

Plastic waste can be contaminated by a range of factors significantly influencing its commercial viability when considering the use of recycled plastic over virgin plastic materials. Contamination can be caused by non-plastic materials such as dust, soil, food, metals, paper as well as print and labels, which can be eliminated with water or a sodium hydroxide solution (Morrison, 2009). Also the combination of different polymers may result in contamination, since mechanical recycling of plastic waste can only be applied to single-polymer plastics (Al-Salem *et.al.*, 2009). However, as stated by Morrison (2009), it is possible to process more than one type of polymeric material if the plastic types under process conditions are compatible with each other. This for example is the case with LDPE and LLDPE. PVC though, should not be recycled with other polymeric types as it requires lower processing temperatures than most other polymers. PVC also liberates hydrochloric acid (HCl), which would degrade the other polymers in the mixture making it unmarketable (Aguado and Serrano, 1999).

The elimination of the contaminants can be achieved by an effective separation process. Separation technologies include automatic sorting (e.g. standard Near Infra Red (NIR) machines), gravity separation (e.g. sink floating) and electrostatic separation, each of them more or less suitable for certain plastic type mixtures (Shent *et.al.*, 1999). A gravity separation for example cannot be applied to a mixture of PVC and PET due to their very slight differences in bulk densities (Shent *et.al.*, 1999). The electrostatic separation process can be inhibited by additives in the plastic, contamination or an insignificant difference in triboelectric charging property. NIR automatic sorting machines are able to separate PET, HDPE, PP, PS and PVC, but fail in identifying black plastics (Dvorak *et.al.*, 2009). Due to the individual conformity of the separation technologies for certain plastic types, a combination of technologies are often applied in practice (Dodbiba *et.al.*, 2008).

As analysed by Dvorak *et.al.* (2009), film and various rigid plastics are contaminated at a level of 37 – 50%. The lowest losses due to contamination were recorded for the bottles because of the comparatively simple identification of the base plastic. Also the losses in the film fraction were relatively low because of the fact that LDPE can cope with the presence of other polymers like HDPE and PP.

Another barrier which might influence a viable mechanical recycling option is the relatively low density of most plastics resulting in the requirement of a high volume of processing (Morrison, 2009). A survey conducted by Scholes *et.al.* (2009) revealed that this is one of the main reasons for an insufficient plastic recycling, after the high processing costs as well as a lack of appropriate collection schemes by Local Services.

However, as explained by Paul Dumpleton, the director of materials management from Shanks Waste Solutions, nowadays sorting machines like NIR and density separators are very high developed, with minimal contamination and maximal separation efficiency. Though, the feasibility of a separation machine is dependent on the volume and the composition of the waste and has to be evaluated in each individual case.

2.3.3 Markets and prices of recovered plastics in UK

Sorting, cleaning and preparation technologies are being improved through investments in technology leading to a higher quality material. However, the barrier to such investments is the uncertain end market for the recycled materials. According to Defra (2007), the end markets for recycled mixed plastic in the UK are generally limited.

Firstly, there is a reduced domestic capacity for reprocessing mixed plastic waste and secondly, the capabilities for using recycled plastic in manufacturing processes and producing new products are also still in early development. Therefore, a high quantity of recycled plastic is exported, mainly to China (WRAP, 2007). Only after the Chinese market collapsed in the autumn of 2008, companies such as Greenstar, AWS Ecoplastics and Closed Loop started to invest in modern sorting, washing and reprocessing techniques (Morrison, 2009). Recent businesses also show an interest in taking post-consumer recycled plastic (Morrison, 2009). However, the UK market for recycled plastics is still very much dependent upon China's demand (Letsrecycle, 2010c).

In the UK, recovered plastic is mostly recycled in the form of 'open loop' as compared to 'closed loop' meaning that the recycled plastic is used in a different application from the starting product (Wrap, 2007). Recycled HDPE, for example is used to produce pipes, pots, and other moulded products whereas films are principally remanufactured into sacks and bags; recovered PET is used in the polyester fibre industry. Since the UK has no capacity for the latter, PET is mainly exported (Wrap, 2007). However, new capacities are going on-line for PET processing, even in the form of the 'closed loop' bottle-to-bottle treatment (Closed Loop Recycling, 2010). Additionally, as stated by EuPC *et.al.* (2009), in 2008 two new plants capable to produce food grade HDPE pellets from recycled HDPE milk bottles came on screen. This is contributing to the current steady increase in the demand of PET bottles, both at a domestic as well as overseas level. According to Letsrecycle (2010d), the prices of recovered PET bottles reached the highest level in June 2010 since late 2000, ranging between £230 and £260 per baled tonne.

As explained by EuPC *et.al.* (2009), it is more common for Material Recycling Facilities to sort the plastic and then send to a reclaimer. There the plastic material is subject to further grinding, washing, drying and sometimes extruding, so that it can be used to replace virgin material.

The prices of recycled plastics have been more volatile than the prices of recycled paper or glass over the last decade. This is due to the fact that the market of recovered plastic is especially sensitive to fluctuations in crude oil prices (Defra, 2007). If the price of crude oil is high, the production of virgin plastics becomes expensive since the main raw material of plastic consists of the by-products of the oil refining industry. This results in an increasing demand for recovered plastic, subsequently increasing the price of recycled plastic (Fathom Consulting, 2008). Consequently, if virgin plastic prices are high, there is a potential for recycled polymers to be competitive. Figure 6 shows the fluctuations of recovered HDPE prices over the last five years reflecting the volatility of crude oil. Prices of virgin and recycled plastics are also very variable in the short term as can be seen in Figure 7, where the price of virgin resin PP is recorded starting from June 2009 until May 2010.

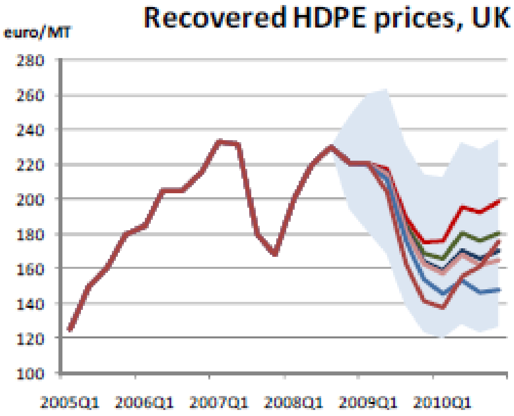

Figure 6: Prices of recycled HDPE in the UK
(Fathom Consulting, 2008)

Figure 7: Price of virgin resin PP Copolymer
(The plastics exchange, 2010)

Since 1999, according to Fathom Consulting (2008), oil price has raised from $ 20/barrel to $ 130/barrel in 2008 and has fallen dramatically after the global recession by early 2009. From then onwards there was again an increase until April of this year reaching $ 90/barrel and it is now priced at $ 74/barrel (29th May 2010) (Oil-price.net, 2010). This trend is reflected in the prices of virgin as well as recycled plastics.

The prices of recycled plastic vary depending on the type of polymer, quality and colour. Table 5 illustrates UK prices of baled plastic film for delivery to an established merchant business.

PLASTIC FILM – BALED	August 2010 (in €/tonne)
Printed / coloured	290 / 320
Clear / natural	415 / 465

Table 5: Prices of used plastic film for recycling
(Letsrecycle, 2010b)

Table 6 indicates UK prices of used plastic bottles for delivery to a merchant serving the UK or to a UK reprocessor for recycling.

PLASTIC BOTTLES	**August 2010 (in €/tonne)**
Clear and light blue PET	305-340
Coloured PET	135-160
Natural HDPE	380-430
HDPE mixed colour	195-245
Mixed	170-220

Table 6: Prices of used plastic bottles for recycling
(Letsrecycle, 2010c)

2.3.4 Markets and prices of recovered plastics in Austria

In Austria, the recycling market and capacity seems to be more advanced than in the UK. The necessary operational and logistical steps from the point of waste arising to the reprocessing into new products are more developed and coordinated between each other. Compared to the UK, there are more plastic reprocessors, both, "closed loop" recycler such as PET to PET and "open loop" recycler. As stated by Plasticker (2010), the capacities of the recycling companies are not fully depleted. Examples of plastic recycling companies are given in the following list:

- PET to PET Recycling Österreich (http://www.pet2pet.at/)
- Zentralplast Kunststoffrecycling (www.zentralplast.at)
- Joachim Puhm (www.puhm.eu)
- Reststofftechnik (www.reststofftechnik.at)
- ARG Alt- und Kunststoff-Recycling (www.arg-recycling.at)
- Walter Kunststoff Recycling (www.wkr.co.at)

After stagnation of the market of recycled plastic starting in August 2008, it has been recovering since the second quarter of 2010. Baled plastic, regranulate and ground stock can again be sold at a higher price due to an increased demand of the plastic processors (BVSE, 2010). High quality recycled plastic can be purchased favourably as compared to virgin plastic. However, plastic recyclers complain about poor quality material and have problems in accepting secondary plastic for recycling (BVSE, 2010). In contrast, plastic waste is very favoured by thermal treatment plants due to the high inherent energy value of the material. Thermal treatment plants also do not work to full capacity and lower the price of the treatment. As consequence, waste management companies refrain from sorting out high quality plastic from the mixed waste (BVSE, 2010).

Table 7 shows the market value of recycled plastic in the month of August 2010 (Plasticker, 2010). However, it has to be pointed out that by May 2010 the prices of various plastic types were between 10 and 50 € lower. Compared to the year 2008, the price ranges of the plastic types are much smaller which suggests a more consistent quality of recycled plastic.

Polymer type	**In €/tonne**
HDPE baled	450
LDPE baled	350
PP baled	290
PET clear baled	415
PET coloured baled	240
PS ground stock	600
W_PVC ground stock	310

Table 7: Prices of recycled plastic in August 2010

(Plasticker, 2010, currency rate from 23rd August 2010)

2.4 Plastic thermal conversion processes

2.4.1 Thermal conversion technologies

The alternative to the recycling of plastic waste is to combust them utilising their energy value and producing electricity and/or heat. Energy recovery from untreated household wastes has been applied for many years in industrialised countries (Porter and Roberts, 1985). According to Malkow (2004), incineration is the most prevailing heat treatment technology for recovering energy from waste in Europe. In recent years, advanced thermal treatments such as gasification and pyrolysis, which are briefly discussed in this chapter, have been installed, so far mainly in Scandinavia and Germany as well as Japan and North America (Heermann *et.al.*, 2001).

According to Clayton and Henrisson (2007), in the UK there are 17 waste incinerators with electricity outputs between 3 and 32 MW and operating with efficiencies in the range of 14 and 27%, if solely electricity is generated. The efficiency can be significantly increased if both heat and power are utilised. While the electricity can be distributed into the national grid, the heat can be supplied to consumers as low grade heat for district heating. A combined heat and power plant (CHP) operates with efficiencies between 70 and 90% (ERA Technology, 2008). Due to its advantageous efficiency performance the UK government sees high potentials in the extension of CHP plants (Enviros Consulting, 2007a).

Gasification and pyrolysis, known as advanced thermal treatments, also take advantage of the energy value of waste materials generating gaseous or liquid fuels.

The gasification process, where a carbonaceous feedstock is heated with a limited oxygen supply, produces a combustible syngas composed of H_2, CO, CO_2 and CH_4, a small amount of tars and oils as well as a small portion of char containing carbon, heavy metals and other inert material. The syngas is principally used to produce electricity, either in a combustion engine or a gas turbine. The simplest way of recovering energy from the syngas is by combustion in a boiler, representing also the sole option able to cope with lower quality syngas (Ali, 2003).

Pyrolysis is the initial stage in a combustion process where only the volatile compounds of the fuel are released forming a syngas, or in condensed form, pyrolysis oil. Char composed of fixed carbon is also generated. In order to avoid the following gasification process, no oxidising agent is supplied to the pyrolysis process (Demirbas and Arin, 2002). Typically, pyrolysis oil is combusted directly in a boiler. However, it can potentially be used as feedstock in the chemical industry, which is not fully technically developed though. The latter could be classified as a recycling rather than energy recovery treatment, which would be beneficial in terms of achieving the recycling targets (Demirbas and Arin, 2002).

2.4.2 Thermal conversion of plastic and operational issues

Plastics provide a beneficial energy source due to their high calorific value (cv). Table 8 shows the calorific value of different polymer types and compares them with typical energy fossil fuels as well as MSW.

Item	**Calorific Value (MJ/kg)**
HDPE	46.4
LDPE	46.6
PP	46.4
PS	42.0
PVC	22.8
Gas oil	45.2
Household Plastic Solid Waste mixture	31.8

Table 8: Calorific value of plastic types, oil, and household PSW mixture
(modified from Sorum et.al., 2001 and Al-Salem et.al., 2009)

The incineration of plastic wastes successfully destroys foams and granules as well as harmful blowing agents like CFCs. However, several environmental problems are associated with the energy recovery of plastic wastes (Al-Salem *et.al.,* 2009). Due to the chemical properties of plastics, which are illustrated in Table 9, harmful emissions to the air can be generated by burning plastic waste. These include the greenhouse gas CO_2 as well as NO_x and SO_x but also volatile organic compounds (VOCs) and heavy metals.

In the emitted particles from the incineration of polymers like PVC, PET, PE and PS, also carcinogenic substances like polycyclic aromatic hydrocarbons (PAHs) and dioxins have been identified (Al-Salem *et.al.,* 2009).

Clean up systems have also to tackle hydrogen chloride (HCl), an acid, which is generated mainly by PVC, having a Cl content of 47.7 wt(%).

Type	**Proximate analysis**			**Ultimate analysis**					
	VM	Fix-C	Ash	C	H	O	N	S	Cl
HDPE	100	0.0	0.0	86.1	13.0	0.9	n.a.	n.a.	n.a.
LDPE	100	0.0	0.0	85.7	14.2	0.05	0.05	0.0	n.a.
PP	100	0.0	0.0	86.1	13.7	0.2	n.a.	n.a.	n.a.
PS	99.8	0.2	0.0	92.7	7.9	0.0	n.a.	n.a.	n.a.
PVC	94.8	4.8	0.4	41.4	5.3	5.83	0.04	0.03	47.7
PET				62.5	4.14	33.1	0	0	0

Table 9: Proximate and ultimate analysis of plastics in wt% ***(n.a. = not available)***
(Sorum *et.al.,* 2001 and Al-Salem *et.al.,* 2009)

According to the chemical and physical characteristics of the feedstock, different reactor types and operational conditions can be applied. It has been proven, for example, that a fluidised bed gasifier can cope better with different feedstock sizes, densities and ash contents as moving or entrained flow gasifiers (Ali, 2003). Different plastic polymers are ideally converted at different temperatures as well as different residence times. Sorum *et.al.*, (2001) revealed that PVC is degraded at temperatures between 200 and 525 °C whereas PS, PP, LDPE and HDPE degrade in a range of 350 – 500 °C.

When considering thermal conversion as a treatment option for plastic wastes, the calorific value plays an important role in terms of thermal efficiency and economic feasibility. In regard to the environmental performance, chemical elements such as N, S, Cl as well as the ash content must not exceed a certain level. Other parameters such as heavy metals and aromatic hydrocarbons contained in the plastic are also essential for a detailed chemical analysis (EU Directive 2000/76/EC).

2.4.3 Existing markets in UK

In the UK, only a small proportion is treated by incineration due to the large public opposition to this technology (Enviros Consulting, 2007a). This is the case even if modern incinerators are constrained to comply with the stringent emission limits set by the Waste Incineration Directive (WID), which have been proven to pose only minimal risks to public health (Porteous, 2005). Public perception might possibly be less negative in terms of advanced thermal treatments (ATT), where the feedstock is combusted only partly because their crude definitions mean that they are not incineration and therefore public don't seem to mind them (Heermann *et.al.*, 2001). Enviros Consulting (2007b) is funding small to medium scale demonstration plants throughout the UK in order to give to the public a clear and constructive clarification. ATT are considered to fit well into the government's waste policy. According to Heermann *et.al.,* (2001) a series of new gasification and pyrolysis plants in the form of small- to medium-sized facilities are proposed in the following years.

In terms of the value of plastic wastes as a fuel, it will probably become more and more valuable and be considered as a useful fuel resource rather than as an unnecessary waste that is expensive to dispose of.

2.4.4 Existing markets in Austria

The waste management situation in Austria is strongly characterised by the landfill directive which bans the disposal of untreated waste into landfills since 2004. Since 2004, the thermal pre-treatment of waste has become very significant in Austria (Umweltbundesamt, 2010). The incineration of waste has increased from 880,000 tonnes in the year 2000 to 1.8 million tonnes in the year 2005 (Umweltbundesamt, 2006). In Austria, nine waste incineration plants were online in 2009 with a capacity of 1.9 million tonnes and other six plants were under construction or in planning stage with a capacity of other 940,000 tonnes. According to Greenpeace (2009), Austria is not generating enough waste to use the incineration plants to full capacity and waste would have to be imported. This is contrary to the determined "principle of closeness". Waste is incinerated not only in conventional waste incineration plants but also in industrial plants in the form of co-incineration using certain waste fractions with a high calorific value. All incineration plants fulfil the requirements set by the WID, which has been converted into the “Abfallverbrennungsverordnung” (AVV) in Austria (Umweltbundesamt, 2010).

2.5 Environmental performance of recycling vs. energy recovery

There is a lot of research going on in the field of environmental performance of waste management technologies as well as whole waste management strategies and concepts. Also the question of whether recycling, energy recovery, landfill or a combination of different treatment options of plastic waste performs environmentally best has been investigated by many researchers and waste institutes (Michaud *et.al.*, 2010; Shonfiled, 2008b; Patel *et.al.,* 1999; Eriksson and Finnveden, 2009).

Studies, where the environmental performance was evaluated via a Life Cycle Analysis (LCA), revealed that mechanical recycling performs environmentally better than incineration (Michaud, *et.al.*, 2010; Shonfiled, 2008; Patel *et.al.,* 1999). This is mainly because of the avoidance of the production of virgin plastic. The poor performance of incineration derives from the high emissions of greenhouse gases contributing to climate change. Since plastics are composed of fossil fuels there are no emission savings when offset against the UK energy mix. According to Michaud, *et.al.* (2010), the incineration of plastics with a low calorific value like PVC performs even worse than landfilling. This is due to the fact that in order to supply the same energy amount as one tonne of plastic with a higher calorific value, next to one tonne of PVC, other fossil fuels have to be converted into energy emitting greenhouse gases, too. Pyrolysis, on the contrary, shows significant environmental benefits if compared to incineration and in terms of the energy demand it is even better than mechanical recycling. This is due to the fact that pyrolysis gains considerable primary energy savings from the avoidance of the production of petrochemical products (Michaud *et.al.*, 2010). Thus, these LCA studies act on the assumption that the pyrolysis products are for the usage in the chemical industry rather then for combustion. In the case of the latter, the emissions would be higher and the overall performance probably more similar to the incineration option.

However, also the environmental performance of mechanical recycling varies significantly according to several factors. One of them is the efficiency of the sorting process and the quality of the recycled plastic, respectively. If for example a loss rate of about 40 % is assumed, the environmental impacts of the mechanical recycling option increases significantly (Michaud *et.al.*, 2010). The quality of the recycled plastic has an influence on the substitution rate between recycled and virgin plastic. A substitution rate on a 1:1 basis is very difficult to achieve and implies that the recycled plastic is of a very high quality (Michaud *et.al.*, 2010). If the LCA study is based on the assumption that only 20% of the recyclate replaces virgin plastic, the results change completely, switching from saving emissions to contributing to net impacts (Shonfield, 2008). According to these results it is suggested that the focus should be on developing sorting facilities which are able to deliver high quality plastics. The plastic waste proportion which is impossible to sort out into a high quality fraction cannot be recycled in an environmentally beneficial way.

In order to achieve a high quality recycled plastic, complex and developed sorting facilities like NIR or density sorting machines are required. These consume high amounts of energy, which results in a negative impact on the environment (Shonfield, 2008). The LCA studies based on complex and energy-intensive sorting facilities revealed that mechanical recycling performs worse than incineration in terms of the energy demand (Michaud *et.al.*, 2010). Furthermore, the production of the energy required to operate the machines, which in the UK is based on fossil fuels, is outside the boundaries of these LCA studies. Would the production of this energy with its release of CO_2 emissions be considered, mechanical recycling would perform worse also in terms of the global warming potential and not only in terms of the energy demand.

In fact, a study evaluating the environmental performance not via a LCA but in terms of energy cost savings, found out that recycling of plastic is not a sustainable solution (Lea, 1996). The energy cost saving from mechanical recycling, where separation is assumed to be necessary, is negligible if compared to the recycling of other materials like aluminium or glass. Lea (1996) showed that energy cost savings occur if the energy required to separate, wash and treat wastes is less than the energy consumption needed for the production of virgin products. Lea (1996) emphasised further in his study the significant energy source that is provided by the feedstock of plastics, which favours the energy conversion of the material.

In conclusion, mechanical recycling is generally seen as the environmentally friendliest option if compared to incineration and pyrolysis, especially in terms of climate change (Michaud *et.al.*, 2010; Shonfiled, 2008b; Patel *et.al.,* 1999). However, this is only the case if a high quality recycled plastic can be delivered with a loss rate as low as possible and a substitution rate as high as possible. Additionally, when evaluating recycling as treatment option the energy cost savings have to be considered; if plastic waste can only be recovered with very energy-intensive and complex sorting processes, recycling might not be the environmentally best solution. It is important to distinguish between plastic waste which is recoverable, but not recyclable; and plastic waste which can easily be recycled providing a high quality recyclate.

3 Methodology

The previous chapter reviewed the existing literature and available data in terms of the annual tonnage arising and the physical composition of C&I waste with particular focus on the plastic proportion in UK and Austria. The treatment options recycling and energy recovery for plastic waste were investigated and their limitations and further requirements were discussed. This chapter therefore aims to describe the collection and generation of data required to fulfil the objectives of this research project.

To assess the best economical treatment route for plastics in C&I waste, different research methodologies were applied allowing a comprehensive analysis and considering all the factors which might influence the results. These factors included end markets of recycled plastics and their prices, energy recovery values, waste stream composition, the operational and technical feasibility and the environmental performance. The research methodologies are described below.

3.1 Literature review

A literature review was carried out to understand C&I waste regarding the national arising and physical composition. Existing knowledge about plastic recycling and energy recovery of plastic waste was critically synthesised by reference to academic journals, governmental and regional studies carried out by the Environment Agency of England and Wales, Defra and the UMLFUW, plasicker, as well as actual reports by WRAP and news by Letsrecycle.com.

The literature information was expanded through an expert interview with Paul Dumpleton, the director of materials management from Shanks Waste Solutions, where mainly separation technologies as well as end market availabilities were discussed.

3.2 Site work

Three different waste sites operated by Shanks Waste Solutions were visited in order to obtain an approximate figure of the plastic waste arising by proportion of total waste and composition of plastic types from the commercial and industrial waste stream. The following Table 10 summarises the location and function of each site and the date of each visit.

Site location	**Function of site**	**Dates of visit**
Aylesbury, Buckinghamshire	Material Recycling Facility	27th May 2010
Milton Keynes, Buckinghamshire	Transfer station	2nd and 26th June 2010
Kettering – Northamptonshire	Material Recycling Facility	15th June 2010

Table 10: Location and function of the visited waste sites

In order to analyse the proportion and composition of plastics in C&I waste, an adapted sampling method has been applied, as outlined below:

- A large sample of C&I waste has been spread across the floor (covering a surface area of approximately 35 m^2).
- Black bags of waste were split, emptied and mixed into the waste pile.
- A portion of the mix (approximately 15-20 gardening shovel loads) was removed for hand sorting.
- The sample was sorted by hand into different waste fractions, such as paper, card, organics, wood, glass, metals, and textiles, dense and film plastic and each waste fraction was weighed.
- The plastic fraction was hand sorted by type of plastic and weighed.
- Each plastic type sorted was stored in a container for laboratory analysis.

The left column in Table 11 summarises the plastic types sorted at each site visit; the right column shows the plastic types analysed by the laboratory.

Plastic types sorted at each site visit	Plastic types analysed by the laboratory
HDPE	Film plastic (from previous analysis)
PET	Dense plastic (from previous analysis)
PP	LDPE
PVC	HDPE
PS	PET
Dense non recyclable plastic	PP
Film plastic	PS
Polycarbonate	Dense non recyclable plastic

Table 11: Hand-sorted plastic types and plastic types analysed by the laboratory

3.3 Lab analysis

The plastic samples were analysed by Marchwood Scientific, Southampton for the proximate and ultimate analysis, determining the following:

- Moisture content [CEN/TS 15414]
- Ash
- Volatile matter [CEN/TS 15418]
- Carbon [CEN/TS 15407]
- Hydrogen [CEN/TS 15407]
- Nitrogen [CEN/TS 15407]
- Oxygen [by difference]
- Sulphur [CEN/TS 15407]
- Chlorine [CEN/TS 15408]

The gross calorific value (kJ/kg) and net calorific value (kJ/kg) [CEN/TS 15400] were also determined.

The chemical analyses were the basis for the evaluation of the energy recovery performance as well as environmental issues for each plastic type.

The energy potential of each plastic type or fraction was analysed by the laboratory measuring the gross calorific value and calculating the net calorific value in kJ/kg using the following formula:

$\text{Net cv} = \text{Gross cv} - 212{,}2 \cdot H_{dry} - 0.8(O_{dry}+N_{dry}) \cdot [1-(0.01 \cdot \text{Moisture})] - 24.43 \cdot \text{Moisture}$

$= \text{net cv} \cdot [1-(0.01 \cdot \text{Moisture})] - 24.43 \cdot \text{Moisture}$ (BS EN 14918:2009).

The calorific value can also be expressed as higher heating value (HHV) and lower heating value (LHV). The difference between those results from the heat of evaporation of the water generated by the moisture and hydrogen content of the fuel. For the HHV it is assumed that the energy formed through evaporation is used, while for the LHV it is assumed to be lost (Phyllis, 2009a). By using the Milne formula, the calorific value can be calculated from the elemental composition of the fuel (Phyllis, 2009a):

$\text{HHV as-received (in MJ/kg)}_{\text{Milne}} = 0.341 \cdot C + 1.322 \cdot H - 0.12 \cdot O - 0.12 \cdot N + 0.0686 \cdot S - 0.0153 \cdot \text{ash}$

The LHV can be calculated from the HHV by taking into account the hydrogen and moisture content, as follows:

LHV as-received (in MJ/kg) = HHV as-received – 2.442 [(8.936H/100) + (moisture/100)]

The Milne formula was only used for comparison with the laboratory gross calorific value measured by the laboratory.

Additionally, the chemical parameters were used to calculate the gas composition produced by the incineration of the plastic. The gas composition allows assessment of the environmental performance of the energy recovery option of the different plastic types.

The first step of the calculation consists of the conversion of the elemental components from %weight in moles/hour. Therefore the atomic weights of the selected elements in g/mole have to be considered. Secondly, the air has also to be calculated in moles/hour. Lastly, the species in moles per hour produced by combustion of the plastic can be calculated. For these calculations the following equations have been used for simplification purposes:

a. Carbon dioxide is only carbon containing species formed

   $C + O_2 \rightarrow CO_2$

b. Sulphur dioxide is only Sulphur containing species formed

   $S + O_2 \rightarrow SO2$

c. Molecular Nitrogen (N_2) and Nitrogen oxide (NO) are only Nitrogen (N) containing species formed

d. NO comes from fuel N only

   $N \text{ (fuel)} + \frac{1}{2} O_2 \rightarrow NO$

e. Hydrogen chloride (HCl) is the only Chlorine (Cl) containing species formed

   $H + Cl \rightarrow HCl$

In order to calculate the mass flow in g/hour of all the gases, the moles/hour have to be multiplied by the molecular weight (MW).

3.4 Economic analysis

From the literature review, discussion with Shanks, data acquired at the local waste sites and the chemical analyses of single plastic types, the boundaries of the present study have been defined and different recycling and energy recovery scenarios have been drawn for the economical analysis. Due to operational and environmental issues and end market availabilities, recycling is not suitable for all types of plastics and not every plastic type is suitable for energy recovery. The identification of these plastic types is shown by the economic analysis.

Figure 8 illustrates the general plastic waste management flow sheet for the present study. As the focus is put on the best treatment route for plastic in C&I waste, it is assumed that other waste fractions like metal, aluminium, paper and fines are separated and lie outside the boundaries of the study (see Figure 8 for the whole sorting process). The economical study starts from the point where the plastic fraction is sorted out from the residual waste and treated either via recycling or energy recovery. As illustrated in Figure 8, both the energy recovery and recycling scenario are associated with costs, which are offset against the income. The costs of recycling derive from the separation of plastic while the income comes from the sale of the recycled plastics. The costs of energy recovery derive from operational costs of a power plant while the income comes from the sale of produced electricity or heat.

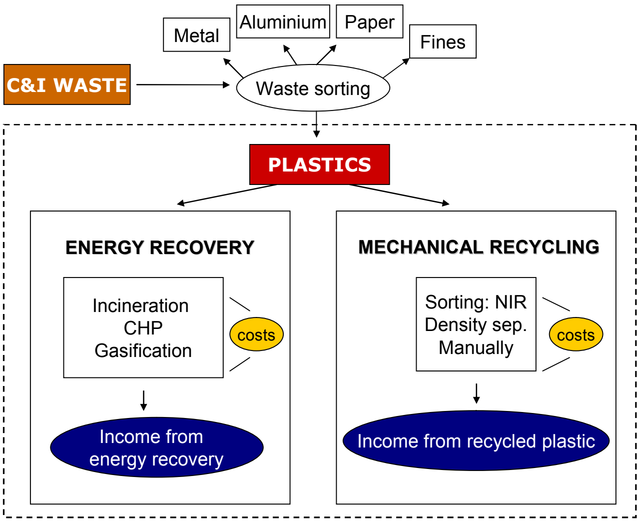

Figure 8: General plastic waste management flow sheet

The flow sheet of a typical Material Recovery Facility (MRF), which has been used as basis for the present study, is illustrated in Figure 9. It shows all the operational separation steps in a typical MRF-order.

All separation steps in Figure 9 which are illustrated in grey are not considered in the comparative analysis as they concern the separation of other waste fractions. Of importance for the present study are the operations highlighted in blue; representing the plastic sorting steps. The separation of dense plastics can either be conducted by a near infrared (NIR) separator, a density separator or manually. The three yellow boxes are the plastic material outcomes of the plastic recovery facility, which are then subject to different treatment options. The different treatment options represent the principal research part of the present study and are analysed by the different scenarios explained below.

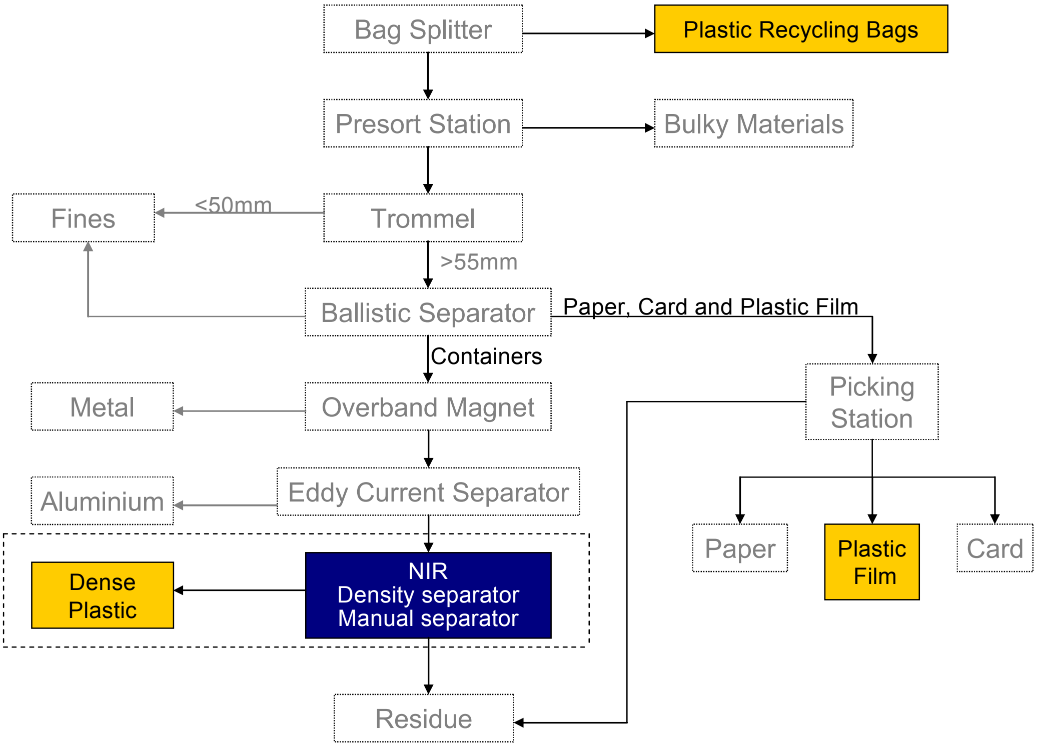

Figure 9: Flow sheet of a MRF

According to the flow sheet, the C&I waste is always first passed through a bag splitter machine which opens the black bags and recovers them. The recovered plastic bags are one of the output stream materials, which are subject to the further analysis. Next, bulky materials are taken out in a pre-sort station, followed by a trommel which separates out the fines. The ballistic separator produces two different waste streams, one consistent of light materials like paper, card and plastic film and one representing rigid, three dimensional materials. The latter is further passed through an overband magnet to sort out metals and an eddy current separator taking out aluminium. The residual waste stream containing mainly plastics is then subject to a further separation step which can either be conducted automatically or manually. The light waste fraction (paper, card and film plastic) emerging from the ballistic separator is forwarded to a manual picking station taking out the film plastics (Mc Dougall, 2001).

The economic analysis principally compares recycling with energy recovery of different plastic types. This comparison is conducted for both countries, Austria and the UK. Furthermore it has been identified whether the treatment options are more economical in Austria or in the UK.

4 Results and Discussion

The following section demonstrates the results from the site visits, the lab testing and the data analysis using the methodology from chapter 3. The results are divided into the composition of the mixed C&I waste fraction and the plastic proportion, the chemical testing results, the gas composition of the various plastic types when burned, the costs and income for both recycling and energy recovery as well as the comparative economic analysis.

4.1 Examined C&I waste in general

The C&I waste examined at the sites was principally composed of the "mixed" C&I waste fraction derived mainly from the public sector, offices, stores, etc. In all the site visits the C&I waste had a very heterogeneous appearance, similar to Municipal Solid Waste (MSW). In Figure 10 the left photo shows a high paper content while in the right photo plastic waste from packaging dominates. These photos were taken after splitting the black bags, emptying them and mixing the contained waste into the pile. Generally, the film plastic, such as black bags and clear films always dominated on first viewing.

Figure 10: Photos of the examined C&I waste

4.2 Plastic fraction in C&I waste

4.2.1 Proportion of plastic waste within the total C&I waste

The proportion of plastics in the total C&I waste, namely about 20%, is very consistent among all the site visits. Figure 11 illustrates the average amounts of all the waste fractions. The biggest fraction is represented by paper, most probably due to the fact that a big amount of the investigated “mixed” C&I waste fraction derives from the public sector and other services including offices; the latter producing mainly paper waste. However, if the proportions of the single site visits are considered, it can be seen that one outlier (50% paper) boosts the average of paper content and probably arises from an office sample. The second biggest fraction is composed of plastics; dense plastic accounting for about 12% and film plastic for about 9%. The other main waste fractions like card, wood, organics, glass, textiles, metals and fines range between 3.5% and 11%. These proportions highly correspond to the findings from previous reports (Dalgleish, 2009, Scholes et.al., 2009, Greifenberg et.al., 2008 and Morrison, 2009), the waste in the present study showing a higher paper and lower cardboard content, less organic and glass and more textiles and ferrous metals.

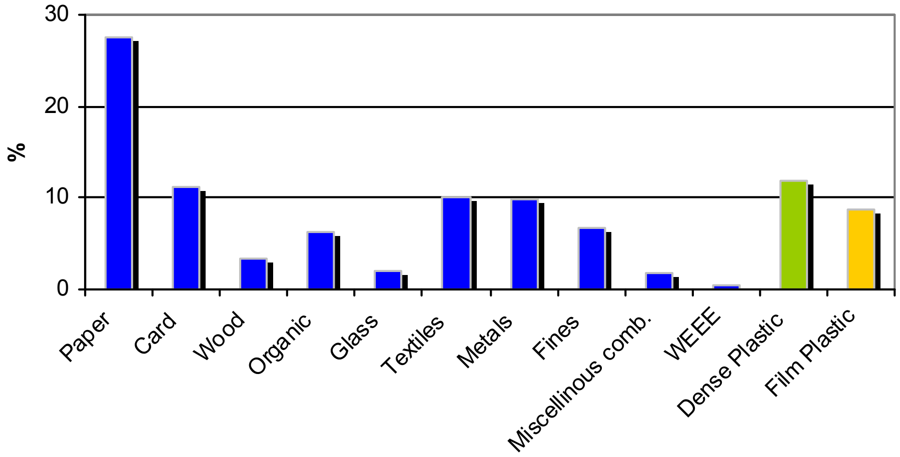

Figure 11: Average proportion of waste fractions in investigated C&I waste

4.2.2 Proportion of film and dense plastic

Overall, the dense plastic proportion is higher than the film plastic, the average accounting for 60%. In two site visits the proportion of dense plastics was even 75%, in one case equal with film plastic and in one site visit the film plastic proportion was considerably higher, accounting for 70%. Figure 12 shows the average proportion between dense and film plastic. The average data does not entirely correspond to the waste survey of Dalgleish (2009), where the film plastic proportion is slightly higher. Also Defra (2007) investigated that out of the total annual plastic waste arising of 5.9 million tonnes, 52.5% are composed of film plastic and 47.5% are dense plastic. However, relating to the actual recovered plastic report of Wrap, the film plastic proportion is lower than the dense plastic proportion (Wrap, 2010b).

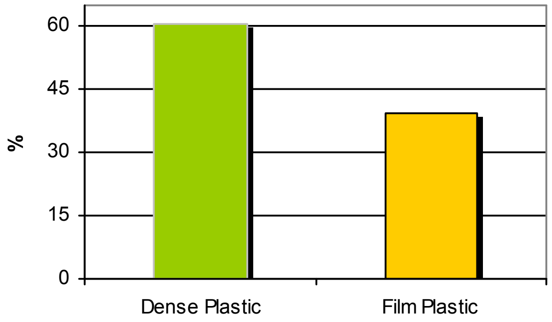

Figure 12: Average proportion of dense and film plastics in investigated C&I waste

4.2.3 Proportion of the different plastic types

On average, the dense non recyclable plastics represent the highest fraction. It is composed of mixed dense plastic which is either not identifiable as a certain plastic type or composed of different, not easily separable plastic types. This fraction accounts for about 20% in three cases and for 50% in one case. The second highest plastic type is represented by HDPE at about 14%, followed by PET with about 8%. Both HDPE and PET mainly consist of plastic bottles and a small amount of other food packaging. PVC represents the next highest plastic type proportion with 7.7%. However, this number derives basically only from one site visit, where PVC material in the form of window frames and pipes has been found. Clearly identifiable PVC like pipes, window frames, flooring, wire coating or floor coverings could not be found in the other site visits. The forth highest plastic type is represented by PP with 4% and followed lastly by PS and Polycarbonate, both account for less than 1% and identified in each case only once. Figure 13 illustrates the average proportion of the single plastic types.

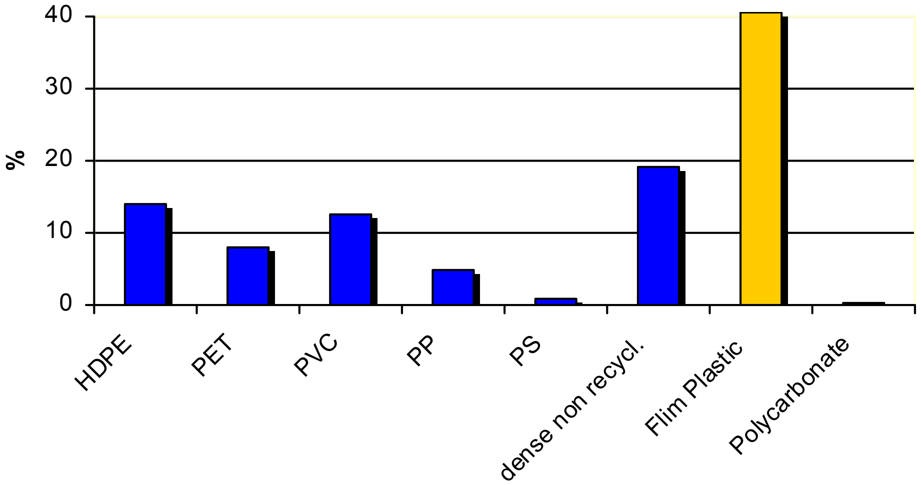

Figure 13: Average proportion of plastic types in investigated C&I waste

In general, the mixed C&I waste was characterised by a very high heterogeneity and it looked quite similar to MSW with a high percentage of black bag waste.

In fact, the investigated dense plastic types show similarities to MSW (Wrap, 2010a). The dense plastic in MSW is mainly composed of plastic bottles (PET and HDPE) and other packaging waste. There is also a small amount of other dense plastic. The plastics of the investigated waste consist to a 27% of packaging waste, to 18% of non recyclable plastic and to 12 % of PVC, which was assumed to account for a higher content. The similarity of the C&I plastic proportion to MSW results probably from the derivation of the mixed C&I waste fraction, being mainly the public sector, including offices and shops. In the investigated C&I waste therefore, the plastic composition is similar to the MSW plastic composition, however showing a bigger percentage of other dense plastics.

In a time period of one month (June), 4 site visits have been conducted. The compositional analysis would be more representative with a greater number of site visits, conducted throughout a longer period of time, considering also different seasons. More accurate information about the composition of plastic types in the mixed C&I waste fraction might modify the conditions under which the plastic types can be treated; for example, it might be better to install a NIR sorting machine if the plastic type which is most easily separable by this technique appears in a high percentage than if it would appear only in a small percentage. However, the waste investigated within the site visits, provides an approximate figure of the composition of mixed C&I waste and its plastic proportion in the local area.

4.3 Chemical analysis

In the following Table 12 the chemical parameters which have been analysed by the laboratory are listed for all the plastic types and fractions.

	LDPE	**HDPE**	**PET**	**PS**	**Non recycl.**	**PP**	**Film Plastic***	**Dense Plastics***
Proximate Analysis								
Total Moisture	0.2	0.3	2.1	2.2	0.2	0.4	2.9	5,7
Ash	0.3	0.9	2.5	1.4	0.7	1	5.4	1,5
Volatile Matter	89.7	87.4	85.2	87.5	87.3	86.5	91.6	89,6
Fixed Carbon	9.8	11.4	10.2	8.9	11.8	12.1	0.1	3,2
TOTAL	100	100	100	100	100	100	100	100
Ultimate Analysis								
Carbon	72.5	73.8	70.2	70	75.8	74.2	78.54	71.2
Hydrogen	4.6	4.5	4.3	4	4.8	4	13.22	10.24
Nitrogen	0.6	0.3	0.4	0.4	0.3	0.5	0.4	0.24
Oxygen**	22.3	21.4	25.1	25.6	19.1	21.3	<0.1	11
Sulphur	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.02	0.07
Chlorine	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.03	0.09
Gross cal.val. kJ/kg	29,000	29,400	30,000	28,800	30,000	29,200	41,300	35,200
Net cal.val. kJ/kg	27,600	27,400	28,000	26,800	27,900	27,200	39,000	33,100

Table 12: Chemical parameters of the hand sorted plastic types

* cleaned and shredded samples

** calculated by difference, may contain other elements

Overall it can be stated, that the measured plastic types show a relatively low moisture and ash content if compared to other typical fuel materials like biomass (treated wood) or coal (bituminous, coal) (Phyllis, 2009b). Also the percentage of fixed carbon is comparatively low while the volatile matter content is high. The content of hydrocarbons is very high in each of the plastic types, carbon accounting for about 73% and hydrogen accounting for about 6%. The S and Cl content is low for all analysed plastic types.

It has to be pointed out that the film and dense plastic shown in the last two columns were tested by the laboratory on cleaned and shredded plastic samples. The other plastic types on the contrary, were analysed in the state and form of collection.

The tests of both the proximate and ultimate analysis have been conducted on the basis of British Standards as referred to in chapter 3.3. Oxygen was the only element which has been calculated by difference. This is critical, as the difference from C, H, N, S and Cl probably includes also other elements, rather then only O.

However, generally the proximate and ultimate analysis show quite strong similarities with the elemental composition from other studies (*Sorum et.al., 2001 and Al-Salem et.al., 2009).* Probably the most significant difference is shown by the content of hydrocarbons, C being about 10% lower and H being about 8% lower in the analysis of the hand-sorted samples from the present study. On the contrary, the amount of O analysed in the studies by Sorum *et.al.* (2001) and Al-Salem *et.al.* (2009) accounts for almost 0 for all plastic types excluding PET. However, since O was not a major parameter in the further calculations, it does not have an impact on the outcome of the economic analysis. Hydrocarbons, on the contrary, have a considerable impact on the calorific value, the higher their amount, the higher the calorific value will be. The comparatively low amount of hydrocarbons in the hand-sorted plastics here will result from the composition and characteristics of the samples. While Sorum *et.al.* (2001) analysed the plastic types as clean, non-coloured samples, the plastics in the present study were analysed in the same composition as collected from the site. Only in the case of PET and HDPE, the paper was removed from the bottles.

For a more complete chemical analysis other halogenated compounds like F and Br, metals like Ni, Cu and Zn and heavy metals like Pb and Cd could have been tested. This would have enabled fuller evaluation of the environmental performance of the plastic types.

The tests demonstrate consistency in the amount of convertible compounds into energy and the suitability of the plastic waste to be used as fuel is obvious in terms of its energy content.

4.4 Energy recovery potential of each plastic type

Table 13 shows the calorific value measured by the laboratory and, in comparison, the HHV and LHV calculated with the Milne formula using the elemental composition of the plastic types (formula described in chapter 3.3). These values, however, have to be treated with caution as the oxygen value might in reality for most plastics types be lower.

Plastic type	Gross calorific value (in kJ/kg)	Net calorific value (in kJ/kg)	Milne (HHV in kJ/kg)	Milne (LHV in kJ/kg)
PET	30,000	28,000	26,100	26,100
HDPE	29,400	27,400	28,400	28,400
LDPE	29,000	27,600	28,000	28,000
PP	29,200	27,200	27,800	27,800
PS	28,800	26,800	25,800	25,800
Dense non recyclable plastic	30,000	27,900	29,800	29,700
Dense plastic*	35,200	33,100	36,200	36,200
Film plastic*	41,300	39,000	43,400	43,000

Table 13: Gross and net calorific value for each plastic type

* cleaned and shredded samples

The measured gross calorific values lay in the range between 28,800 and 30,100 kJ/kg among the plastic types tested without any cleaning or shredding, while the cleaned and shredded mixed dense and mixed film plastics show generally a higher calorific value.

From Table 13 it can be noticed that the calculated heating values do not deviate a lot from the measured calorific values, generally being slightly lower.

Generally, the calorific value of the plastic types is comparatively high resulting in a high energy recovery potential. By comparing the gross calorific value of the plastic types with other typical fuels, it can be noticed that the measured plastics show a higher calorific value than coal (26,000 kJ/kg), wood (19,000 kJ/kg), refuse derived fuel (15,000 kJ/kg) and MSW (10,000 kJ/kg) (Genderbien *et.al.*, 2003).

When calculating the income of the energy recovery option the net calorific value has been used and multiplied by the UK electricity and heat wholesale price. As described in section 3.3, the formula of the net calorific value based on the Standard BS EN 14918:2009 comprises the oxygen content. Since the oxygen is only calculated by difference and not measured directly, it may contain other elements and may therefore be lower. In the hypothetical case of a lower oxygen content the calorific value would be higher and with it the income from energy recovery. However, the difference in the net cv-value caused by a lower oxygen content is assumed to be marginal. The same applies to the HHV calculated with the Milne formula, which also includes oxygen. The higher the oxygen content, the lower the calorific value. Therefore, the HHV calculated with the Milne formula is assumed to be higher due to the probable lower oxygen content.

It also has to be pointed out that the energy recovery outcome depends considerably on the efficiency of the power plant. For the present study, efficiency values based on the current state of art have been applied. With the rapid technical progress, efficiency is supposed to increase in future, making the energy recovery potential even higher.

4.5 Gas composition produced by the combustion of the fuel

The gas composition which is produced by the combustion of the plastic material has been calculated for each plastic type in order to judge the environmental performance of the energy recovery option. The following assumptions were made for these calculations:

- Air to fuel ratio = 20 kg : 1kg
- Solid fuel feed rate = 1 kg/hour
- Composition of the air = N_2: 79%
  O_2: 21%

The following Tables show the emissions in moles/hour and in %volume for each plastic type. Additionally, the mass flow in g/hour is calculated and highlighted in red for each plastic fraction. When the %volume is calculated, it is assumed that the gases are ideal gases having the same molar volumes and therefore being proportional to the moles/hour.

	LDPE				**Film Plastic (cleaned and shredded)**			
	Moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)
CO_2	60.42	8.46	44.00	2,658.48	65.45	8.96	44.00	2,879.80
H_2O	23.10	3.23	18.00	415.85	67.71	9.27	18.00	1,218.71
O_2	66.07	9.25	32.00	2,114.24	32.61	4.46	32.00	1,043.52
NO	0.43	0.06	30.00	12.90	0.29	0.04	30.00	8.70
N_2	564.29	78.99	28.00	15,800.12	56.29	77.26	28.00	15,800.12
SO_2	0.02	0.00	64.00	1.28	0.01	0.00	64.00	0.38
HCl	0.02	0.00	36.50	0.55	0.01	0.00	36.50	0.29
TOTAL	714.35	100.00		21,000.41	730.36	100.00		20,951.52

Table 14: Gas composition of film plastics

By comparing the two film plastic fractions, it can be noticed that the gas composition varies only in terms of the amount of water released. While the cleaned and shredded film plastic emits 1,219 g of H_2O per hour, the film plastic analysed as hand-sorted releases only 416 g of H_2O per hour. This is due to the higher contents of moisture and hydrogen in the case of the cleaned and shredded film plastic. In terms of the overall gas composition, the harmful substances are emitted only in a small amount.

	Dense Plastic (cleaned and shredded)				**Dense non recyclable**			
	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)
CO_2	59.30	7.63	44.00	2,609.20	63.16	8.14	44.00	2,779.04
H_2O	54.34	6.99	18.00	978.17	24.09	3.11	18.00	433.62
O_2	99.40	12.78	32.00	3,180.80	123.88	15.97	32.00	3,964.16
NO	0.17	0.02	30.00	5.13	0.21	0.03	30.00	6.30
N_2	564.29	72.57	28.00	15,800.12	564.29	72.75	28.00	15,800.12
SO_2	0.02	0.00	64.00	1.41	0.02	0.00	64.00	1.41
HCl	0.02	0.00	36.50	0.88	0.02	0.00	36.50	0.73
TOTAL	777.55	100.00		22,575.71	775.67	100.00		22,985.38

Table 15: Gas composition of dense plastic from previous studies and dense non recyclable plastic

The gas composition of cleaned and shredded mixed dense plastics does, similar to the cleaned and shredded film plastics, emit a relatively high amount of H_2O while other substances lie in an average range.

	HDPE				**PET**			
	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)
CO_2	61.50	7.90	44.00	2,706.00	58.50	8.19	44.00	2,574.04
H_2O	22.64	2.91	18.00	407.52	22.64	3.17	18.00	407.52
O_2	130.15	16.71	32.00	4,164.80	68.11	9.54	32.00	2,179.52
NO	0.21	0.03	30.00	6.30	0.29	0.04	30.00	8.58
N_2	564.29	72.45	28.00	15,800.12	564.29	79.05	28.00	15,800.12
SO_2	0.02	0.00	64.00	1.41	0.02	0.00	64.00	1.41
HCl	0.02	0.00	36.50	0.73	0.02	0.00	36.50	0.73
TOTAL	778.83	100.00		23,086.88	750.67	100.00		22,364.59

Table 16: Gas composition of HDPE and PET

The gas compositions of PET and HDPE do not show any particular values apart from O_2 of PET being comparatively low with 9.5%vol.

	PS				**PP**			
	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)
CO_2	58.30	7.42	44.00	2,565.20	61.83	7.94	44.00	2,720.52
H_2O	21.19	2.70	18.00	381.42	20.19	2.59	18.00	363.42
O_2	14.59	18.02	32.00	4,530.88	131.67	16.92	32.00	4,213.44
NO	0.29	0.04	30.00	8.58	0.36	0.05	30.00	10.71
N_2	564.29	71.82	28.00	15,800,12	564.29	72.50	28.00	1,.800.12
SO_2	0.02	0.00	64.00	1,41	0.02	0.00	64.00	1.41
HCl	0.02	0.00	36.50	0,73	0.02	0.00	36.50	0.73
TOTAL	785.70	100.00		23,288.34	778.38	100.00		23,110.35

Table 17: Gas composition of PS and PP

The gas composition of both PS and PP do not show any special values and are comparable with HDPE, dense non recyclable plastic and film plastics from the present study.

	PVC			
	moles/hour	% vol	MW (g/mole)	Mass flow (g/hour)
CO_2	34.50	4.26	44.00	1,518.00
H_2O	20.33	2.51	18.00	365.94
O_2	177.26	21.89	32.00	5,672.32
NO	0.03	0.00	30.00	0.86
N_2	564.29	69.68	28.00	15,800.12
SO_2	0.01	0.00	64.00	0.58
HCl	13.44	1.66	36.50	490.56
TOTAL	809.86	100.00		23,848.37

Table 18: Gas composition of PVC (data based on literature)

Since PVC has not been analysed by the laboratory within the present study, proximate and ultimate analysis data have been taken from the literature (Sorum *et.al,*, 2001) in order to calculate the gas composition. Accordingly, PVC emits a high amount of HCl at 13 moles/hour or 490 g/hour respectively. In addition, PVC releases a relatively low amount of CO_2 due to the low carbon content of 41%.

Overall, the different plastic types show relative similar gas compositions; the cleaned and shredded mixed dense and film plastics showing a relatively high H_2O amount and PVC showing very high HCl-emissions.

According to the EU Waste Incineration Directive (WID), the emission level of HCl accounts for 10 mg/m^3 and of SO_2 for 50 mg/m^3 (EU Directive 2000/76/EC, 2000). The emissions for HCl and SO_2 have been converted from mole/hour and g/hour into mg/m^3 in order to determine if the emissions caused by the incineration of the various plastic types comply with the emission targets of the WID.

In order to conduct the conversion, the molar volume of 22.414 L/mole has to be multiplied by the emission in moles/hour in order to get L/hour. Next, the L/hour value has to be multiplied by 0.001 m^3/L in order to get the emission value in m^3/hour. Finally, the emission level in g/hour, which has been calculated in the gas composition calculation, has to be divided by the m^3/hour value in order to get the required emission value in g/m^3.

The emission levels in the WID apply at a certain content of oxygen, for waste fuel being 11%. Therefore, the calculated emission level in g/m^3 has to be multiplied by a conversion factor in order to adjust the oxygen content of the plastic fuel to the 11%. The conversion factor results from the division $(21-O_S)/(21-O_M)$. O_S stays for the 11% oxygen set by the WID and O_M stays for the oxygen content of the specific fuel (EU Directive 2000/76/EC, 2000).

The results are given in Table 19.

	WID emission level	LDPE	Film pl. (cleaned, shredded)	Dense pl. (cleaned, shredded)	PVC	HDPE	PET	PS	non recycl	PP
SO_2 (mg/m3)	**50.00**	2.40	1.03	3.93	25.88	7.87	2.90	10.50	6.3	7.87
HCl (mg/m^3)	**10.00**	1.02	0.78	2.45	16.30	4.07	1.50	6.50	3.9	4.07

Table 19: SO_2 and HCl emissions in g/m3 for each plastic type

PVC does not comply with the emission targets set by the WID as it causes 16.3 mg/m^3 while only 10 mg/m^3 are allowed. All the other plastic types do not exceed the emission levels and do therefore not pose any serious risk to human health (Porteous, 2005).

However, the findings in respect of the gas composition have also to be treated with caution, because the amount of O_2 released might in reality be lower. However, the environmentally more relevant emissions HCl and SO_2 are calculated from the elements S and Cl, which were measured directly and their outcomes are considered to be reliable.

The calculation of the gas composition of the single plastic types does not provide a deeper understanding of the environmental performance, neither for the energy recovery option, nor for a comparative analysis between recycling and energy recovery. However, this was not the aim of the present study. The gas composition analysis was conducted with the purpose to determine if energy recovery could at all be an option in terms of the compliance with the Waste Incineration Directive. For a complete environmental evaluation of both recycling and energy recovery of plastic types, a Life Cycle Assessment (LCA) which calculates the environmental impact of all operational steps, has to be conducted. This was done by many scientists concluding that generally recycling demonstrates the environmentally better option than energy recovery (Michaud, *et.al.*, 2010; Shonfiled, 2008; Patel *et.al.,* 1999). However, the outcomes depend heavily on the system boundaries, i.e. the operational steps and parameters (e.g. the sorting efficiency).

4.6 Potential income

This section discusses the potential energy recovery income based on the electricity and heat wholesale prices in the UK and in Austria and the market value of recycled plastic respectively.

4.6.1 Potential energy recovery income

The income from the energy recovery of the plastic materials arises from the electricity wholesale price in £/kWh or €/kWh. This price was £ 0.055/kWh in March 2010 (€ 0.062/kWh) in UK (Nutel Energy Ltd, 2010) and € 0.073/kWh (E-control, 2010) in March 2010 in Austria.

In order to determine the potential price of the energy recovery of 1 kg of plastic waste, the calorific value in kJ/kg of each plastic type has to be converted into kWh/kg.

Since 1 J corresponds to 1 Ws, the value of the calorific value has to be multiplied by 0.000278 to convert kJ/kg into kWh/kg. For the potential energy recovery income the efficiency of the plant has to be taken into consideration by subtracting the loss percentage of the energy conversion. Lastly, the calculated kWh/kg with the considered plant efficiency, have to be multiplied by the electricity wholesale price to get €/kg of plastic material. By multiplying this amount with 1,000 the potential income per tonne of plastic type can be calculated.

The same calculation has to be done for the income from the produced heat in the case of incineration with CHP by multiplying the kWh/kg with the heat sale price. The heat sale price was € 0.078/kWh in August 2010 (Macadam, *et.al.,* 2009). This data is taken for both, the UK and Austria.

The energy recovery income calculations are based on some assumptions regarding the power plant efficiency as listed in Table 20:

	Power plant type		
	Incineration with CHP*	Incineration with electricity**	Gasification**
Overall efficiency	80	20	40
Electrical efficiency	30		
Thermal efficiency	50		

Table 20: Plant efficiency assumption or the energy recovery options

* Source: Macadam, *et.al.*, 2009

** Source: Personal communication with Simms, N., Energy Technology, Cranfield University

Taking the LDPE as example, the calculation for the incineration scenario with CHP is shown in Table 21 and described underneath.

	CHP	LDPE
		net cv
	kJ/kg	**27,556**
	kWh/kg	7.66
Efficiency assumption	Overall efficiency (%)	80.00
	Electrical efficiency	30.00
	Thermal efficiency	50.00
Electricity	kWh/kg with elect. Efficiency	2.30
	Price in €/kWh	0.062
	Income (€/kg)	**0.142**
	Income from electricity (€/tonne)	**142.49**
District heating	kWh/kg with thermal efficiency	3.830
	Price in €/kWh	0.078
	Income (€/kg)	0.299
	Income from heat (€/tonne)	**298.76**
	TOTAL INCOME (€/tonne)	**441.25**

Table 21: Energy recovery income calculation of film plastic

LDPE has a net calorific value of 27,556 kJ/kg which corresponds to 7.66 kWh/kg, when multiplied by 0.000278. The incinerator with CHP is assumed to have an overall plant efficiency of 80%, the electrical efficiency accounting for 30% and the thermal efficiency accounting for 50%. Therefore, the 7.66 kWh/kg have to be multiplied by 0.3 in order to get the electrical energy production; this results in 2.3 kWh/kg. By multiplying 2.3 kWh/kg with the electricity wholesale price of € 0.062/kWh, the income € 142.49/tonne is calculated. Additionally, the 7.66 kWh/kg have to be multiplied by

0.7 in order to get the thermal energy production which results in 3.83 kWh/kg. The income for the thermal energy production is € 298.76/tonne (by multiplying 3.83 kWh/kg with € 0.078/kWh x 1,000). The overall income from the energy recovery of LDPE in an incineration with CHP is therefore € 441.25/tonne.

Table 22 lists the income of every plastic type and fraction for the CHP, the EfW with electricity production only and the gasification scenario for UK, while Table 23 for Austria.

	Film pl. (cleaned, shredded)	**Dense pl. (cleaned, shredded)**	**LDPE**	**PS**	**HDPE**	**Non recycl.**	**PP**	**PET**	**PVC***
Income CHP	625.41	530.18	441.25	428.66	438.41	446.42	435.18	447.64	365.09
Income EfW (electricity)	134.64	114.14	94.99	92.28	94.38	96.10	93.68	96.37	78.60
Income Gasificaiton	269.27	228.27	189.98	184.56	188.76	192.21	187.37	192.73	157.19

Table 22: UK energy recovery income for each plastic type and fraction in €/tonne

* Source of calorific value: Sorum *et.al.,* 2001

	Film pl. (cleaned, shredded)	**Dense pl. (cleaned, shredded)**	**Film plastic**	**PS**	**HDPE**	**Non recycl.**	**PP**	**PET**	**PVC***
Income CHP	617.81	523.74	435.89	423.45	433.09	441.00	429.89	442.20	360.65
Income EfW (electricity)	158.52	134.39	111.84	108.65	111.13	113.16	110.31	113.46	92.54
Income Gasificaiton	317.05	268.77	223.69	217.31	222.25	226.31	220.61	226.93	185.08

Table 23: Austrian energy recovery income for each plastic type and fraction in €/tonne

It has to be pointed out that the electricity and heat wholesale prices fluctuate over time and only small variations would change the potential income considerably. If the electricity wholesale price is considered throughout the period of the last three years, it ranges from cent 3/kWh in April 2007 to more than cent 10/kWh in July 2008, before dropping again and currently accounting for cent 6/kWh (Nutel Energy, 2010). The likely increase of fossil fuels in the future due to a supply shortage, will contribute to higher electricity prices (Sharman and Constable, 2008). In this case any non-fossil fuel generator will enjoy high prices while generators using oil, coal and gas will encounter economical difficulties. Therefore, it can be assumed that when fossil fuels become more expensive, waste is likely to be considered as a fuel resource.

4.6.2 Potential recycling income

The income for the recycling of the plastic waste arises from the market value of recovered baled plastic in €/tonne.

The actual market values are listed in Table 23, both for the UK market and the Austrian market. Data for the Austrian market are taken from a German source, which is considered to be comparable to the Austrian data. Specific market values of recovered plastic in Austria are not available.

Plastic type	UK - €/tonne	AUT - €/tonne
Natural HDPE	405*	450**
Clear PET	335*	415**
Coloured PET	160*	240**
Clear LDPE	430*	350**
PP		295**
PVC ground stock		305**
PS ground stock		635**
Dense non recycl.	0***	

Table 24: Market value of recycled plastic types

* Source: Letsrecycle, 2010b

** Source: Plasticker, 2010

*** Personal communication with Dumpleton, P. from Shanks Waste Solutions (2010)

The income from the recycling of plastic waste depends on the value of recovered plastic. Considering the market value throughout the last two years, it can be observed that it currently is relatively high, ranging between € 160 - 500/tonne for the various plastic bottles and film. However, in the UK, the value lied in a range between € 60 - 180/tonne about one and a half years ago (WRAP, 2010b).

The price fluctuations of recovered plastics make it difficult for waste management companies to implement sophisticated and cost-intensive separation facilities. They are also the reason for the currently relative limited end market availability of recovered plastics in the UK. However, some examples of plastic reprocessing facilities and UK "closed loop" recycling plants for PET bottles suggest, that there are initiatives for supporting plastic recycling and growing belief in its environmental and economical advantages (WRAP, 2010b).

The price of recycled plastic correlates with the price of crude oil, because oil is the main raw material of plastics. Thus, if the oil price increases the production of plastic materials becomes more expensive and recovered plastics more attractive. In the past it was apparent, that the value of recovered plastics decreased with a price decline of crude oil. However, while the world demand for crude oil is increasing rapidly, the OPEC-supply is decreasing at the same time due to diminishing oil reserves. Accordingly, the price of oil rises, as predicted by the International Energy Agency (2010). Therefore, it this trend comes true, recycled plastics will become much more valuable and the income of the recycling option calculated in this study will be accordingly higher.

4.7 Potential costs

The potential costs concern the operational costs of the treatment options, i.e. the costs per tonne of separating plastic waste and of operating a thermal power plant respectively. For UK and Austria the same costs are assumed.

4.7.1 Potential costs of the energy recovery of plastic waste

As previously explained, only the operational costs are considered rather then also the capital costs. Since the income is calculated in €/tonne of recycled or recovered plastic type, the operational costs are also given in €/tonne.

The operational costs of an EfW-plant are assumed to be € 258/tonne (Macadam, *et.al.*, 2009). These costs are valid for both the incinerator with electricity production only and the incinerator with CHP.

The operational costs of a gasifier, on the contrary, are assumed to be 44% higher (Milton Keynes council and Northamptonshire county council, 2008) and account therefore for € 371/tonne.

4.7.2 Potential costs of the recycling of plastic waste

For the operational costs of the recycling option an average figure from the literature has been taken, i.e. € 163/tonne (Wollny *et.al.*, 2002). Wollney *et.al.* (2002) has calculated that the average sorting costs of plastic were about € 430/tonne in the year 1999 and the average costs for further processing for feedstock recycling accounted for € 215/tonne. It has been predicted that in the year 2010 the average costs of sorting and processing will account for € 245/tonne. By considering the sorting and processing costs of the year 1999, € 163/tonne out of the € 245/tonne are caused by sorting.

Additionally, specific costs of different sorting machines and options have been calculated based on the energy consumption of the machines in kW/tonne of plastics.

These specific separation costs were used to compare the different sorting techniques in terms of the economic performance and are described in the following chapter.

4.7.3 Separation costs of plastic waste

The costs of the different separation machines and options were calculated in terms of their energy consumption and by taking into account the separation efficiency.
The costs for the NIR sorter derive from the manufacturer "Pellenc", having a power consumption of 34 kW and a throughput of 3 tonnes/hour (Shonfield, 2008). This results in a power consumption of 11 kWh/hour. This value has to be multiplied by the end user price for UK industrial consumers, accounting for € 0.153/kWh in November 2009 (Europe's Energy Portal, 2010). The costs per tonne when considering only the power consumption, account therefore for € 15.63/tonne. However, the separation efficiency has to be taken into account, which differ according to various plastic types and are shown below:

- PET: 77%
- PE: 67%
- PP: 80%
- PS: 65%
- PVC: 81%

By considering the separation efficiency, the costs in €/tonne of a NIR sorter are shown in Table 24.

The costs for the density separator derive from the manufacturer TLT, which has a power consumption of 15.13 kWh/hour assuming a throughput of 4 tonnes/hour (Shonfield, 2008). By considering the separation efficiency of 70% for each plastic type, the costs in €/tonne account for 29.8 as shown in Table 24.

Finally, the costs for manual separation were calculated by considering the sorting rate per person in kg/hour, which are listed in Table 26 (MC Dougall, 2001) and the hourly salary per person, which is assumed to be € 7.18 (Franchetti, 2009). The results of the costs for manual separation are given in Table 25.

		HDPE	**PET**	**PP**	**PVC**	**PS**	**Film plastic**
NIR	€/tonne	23.33	20.30	19.54	19.54	24.05	-
Density sep.	€/tonne	29.80	29.80	29.80	29.80	29.80	-
Manual sep.	€/tonne	44.90	44.90	44.90	29.93	29.93	360

Table 25: Power consumption costs of different separation techniques for each plastic type

Plastic type	Sorting rate per person (in kg/h)
PET	160
PVC	240
Film	20
HDPE, PP*	160
PS *	240

Table 26: Sorting rate of plastic types in kg/h per person

From Table 25 the NIR sorter is the cheapest sorting technique followed by the density separator and finally by the manual separation option. However, within the scenarios an approximate number for the operational recycling costs has been assumed due to lack of data about all associated costs of the different separation techniques such as amortisation.

4.8 Economic analysis

This section will show the economical performance of both the energy recovery and recycling options of all plastic types by comparing the two treatment options between UK and Austria.

For the energy recovery option the following three scenarios have been calculated:

- Incineration with CHP
- Incineration with electricity production only
- Gasification

One tonne of plastic type was used as functional unit.

The chapter is subdivided into four parts:

- Comparison between recycling and energy recovery in Austria
- Comparison between recycling and energy recovery in UK
- Comparison of recycling between Austria and UK
- Comparison of energy recovery between Austria and UK

4.8.1 Economical performance of recycling vs. energy recovery in Austria

Table 27 and Figure 16 illustrate the results of the economic analysis between energy recovery in a CHP plant and recycling in Austria for HDPE natural, PET clear, PET coloured, LDPE and PP.

	HDPE nat.	**PET clear**	**PET col.**	**LDPE**	**PP**
Recycling	287	252	77	187	132
CHP	206	215	215	209	202

Table 27: Comparison between recycling and CHP in Austria

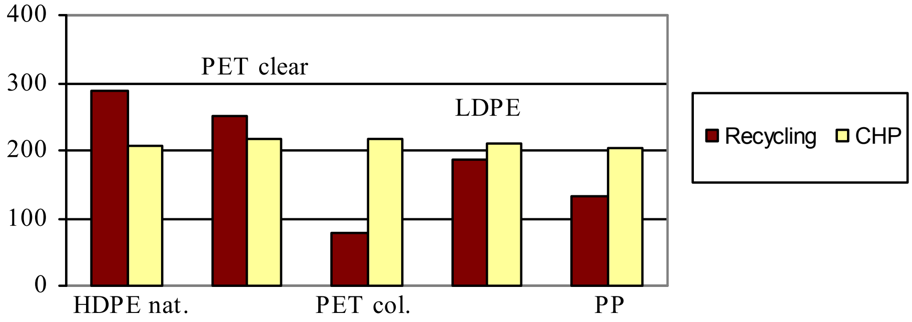

Figure 14: Comparison between recycling and CHP in Austria

By comparing recycling with energy recovery in a CHP plant in Austria, the energy recovery option performs economically better for all plastic types except HDPE natural and PET clear. By recycling of HDPE € 287/tonne can be earned while incineration is worth only € 206/tonne. In the case PET clear, recycling is for € 37/tonne more economical than energy recovery. The energy recovery option results in a revenue of about € 200/tonne for all plastic types and the revenue of recycling varies between the plastic types.

Table 28 and Figure 17 illustrate the results of the economic analysis between energy recovery in a EfW plant with electricity production only and recycling in Austria.

	HDPE nat.	**PET clear**	**PET col.**	**LDPE**	**PP**
Recycling	287	252	77	187	132
EfW (electricity)	-147	-145	-145	-146	-148

Table 28: Comparison between recycling and EfW with electricity production in Austria

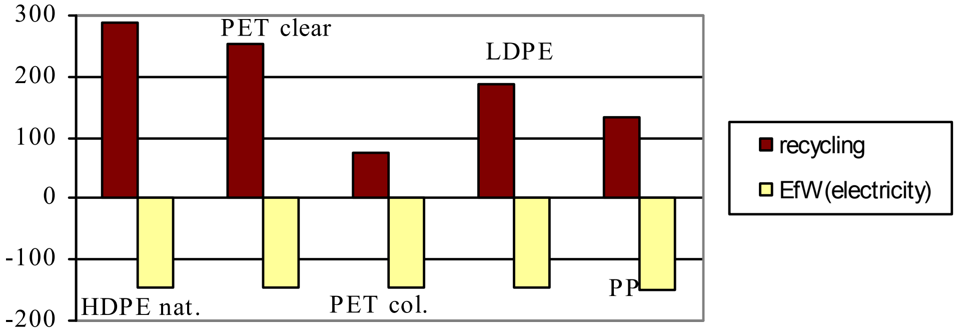

Figure 15: Comparison between recycling and EfW with electricity production in Austria

When recycling is compared to energy recovery in a EfW plant with electricity production only, the recycling option performs economically much better. Incineration with electricity production only results in a loss for each plastic type. This is due to the low plant efficiency of 20% of an incinerator which produces only electricity.

Table 29 and Figure 18 illustrate the results of the economic analysis between energy recovery in a gasifier and recycling in Austria.

	HDPE nat.	**PET clear**	**PET col.**	**LDPE**	**PP**
recycling	287	252	77	187	132
gasification	-149	-144	-144	-147	-150

Table 29: Comparison between recycling and gasifiction in Austria

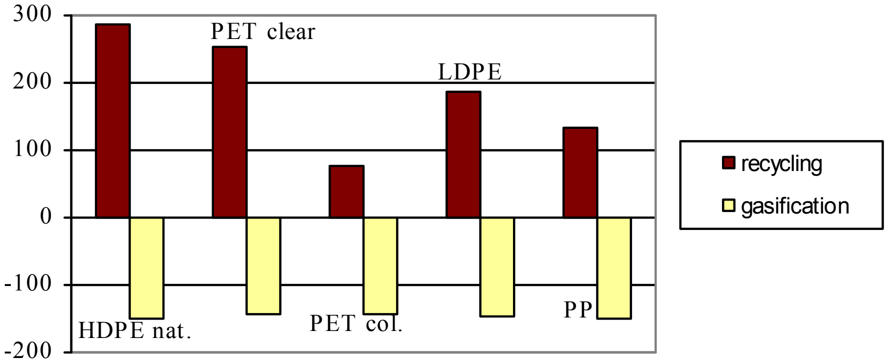

Figure 16: Comparison between recycling and gasifiction in Austria

In Table 29, recycling performs economically clearly better in compared to energy recovery in a gasification plant. The loss of the gasification option is even higher than the loss of the incineration with electricity option. This is due to the higher operational costs of about 40% for the advanced thermal treatment as compared to conventional incineration.

4.8.2 Economical performance of recycling vs. energy recovery in UK

The economically best treatment option of plastic types in UK has been identified by considering the UK-market value of recycled plastic and the electricity wholesale price of UK, respectively.

Table 30 and Figure 18 illustrate the results of the economic analysis between energy recovery in a CHP plant and recycling in UK for HDPE natural, PET clear, PET coloured, LDPE and dense non recyclable plastic.

	HDPE natural	**PET clear**	**PET coloured**	**LDPE**	**dense non rec. Pl.**
recycling	242	172	-3	267	-163
CHP	180	190	190	183	188

Table 30: Comparison between recycling and CHP in UK

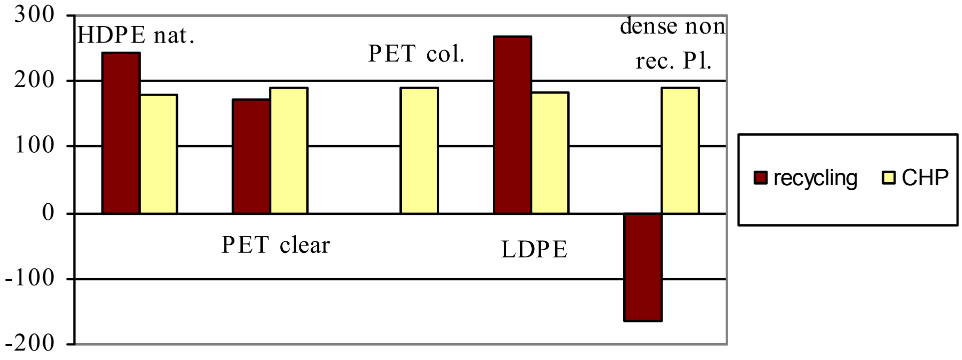

Figure 17: Comparison between recycling and CHP in UK

By comparing the economics of recycling to energy recovery in a CHP plant in UK, energy recovery performs, similar to Austria, better. In the case of PET coloured and dense, non recyclable plastics, incineration in a CHP plant is much more economical than recycling. In the case of PET clear, € 190/tonne can be earned by energy recovery and € 172/tonne can be earned by recycling. HDPE natural and LDPE perform slightly better when recycled.

Table 31 and Figure 19 illustrate the results of the economic analysis between energy recovery in a EfW plant with electricity production only and recycling in UK.

	HDPE natural	PET clear	PET coloured	LDPE	dense non rec. Pl.
recycling	242	172	-3	267	-163
EfW (electricity)	-164	-162	-162	-163	-162

Table 31: Comparison between recycling and EfW with electricity production in UK

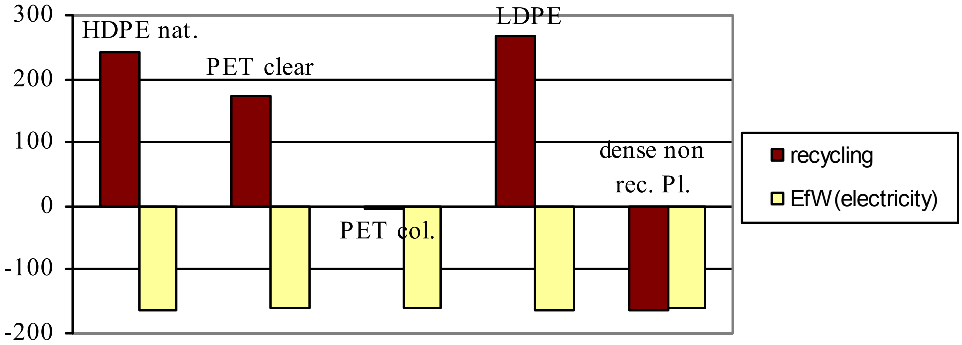

Figure 18: Comparison between recycling and EfW with electricity production in UK

Energy recovery in a Efw plant with electricity production only results in a loss for all plastic types due to the low efficiency of the plant and the accordingly small energy generation. The dense, non recyclable plastic fraction performs better if incinerated rather than recycled.

Table 32 and Figure 20 illustrate the results of the economic analysis between energy recovery in a gasifier and recycling in UK.

	HDPE natural	PET clear	PET coloured	LDPE	dense non rec. Pl.
recycling	242	172	-3	267	-163
gasification	-182	-178	-178	-181	-179

Table 32: Comparison between recycling and gasification in UK

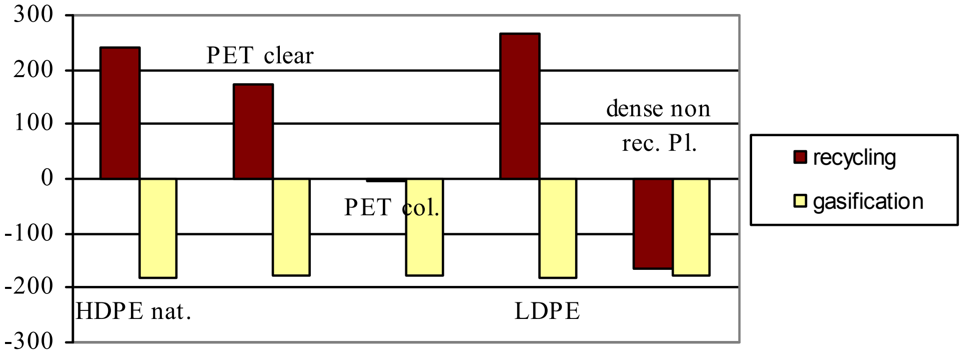

Figure 19: Comparison between recycling and gasification in UK

4.8.3 Economical performance of recycling: comparison between UK and Austria

The economical performance of the recycling option has been calculated by subtracting the costs of plastic separation by the value of recovered plastic. For the separation costs, an approximate figure of € 163/tonne have been used and are assumed to be the same for both countries. The market value of recovered plastic however, is different amongst UK and Austria, as shown in Table 27. Table 27 and Figure 15 illustrate the results of the economical performance of recycling in Austria and UK.

	HDPE natural	PET clear	PET coloured	LDPE	PP	PVC ground stock	PS ground stock
INCOME UK	405	335	160	430			
INCOME AUT	450	415	240	350	295	305	635
COSTS	163	163	163	163	163	163	163
REVENUE UK	**242**	**172**	**-3**	**267**			
REVENUE AUT	**287**	**252**	**77**	**187**	**132**	**142**	**472**

Table 33: Comparison of recycling between Austria and UK

The comparison has been conducted for the plastic types HDPE natural, PET clear, PET coloured and LDPE. For PP and PVC no UK-prices were available.

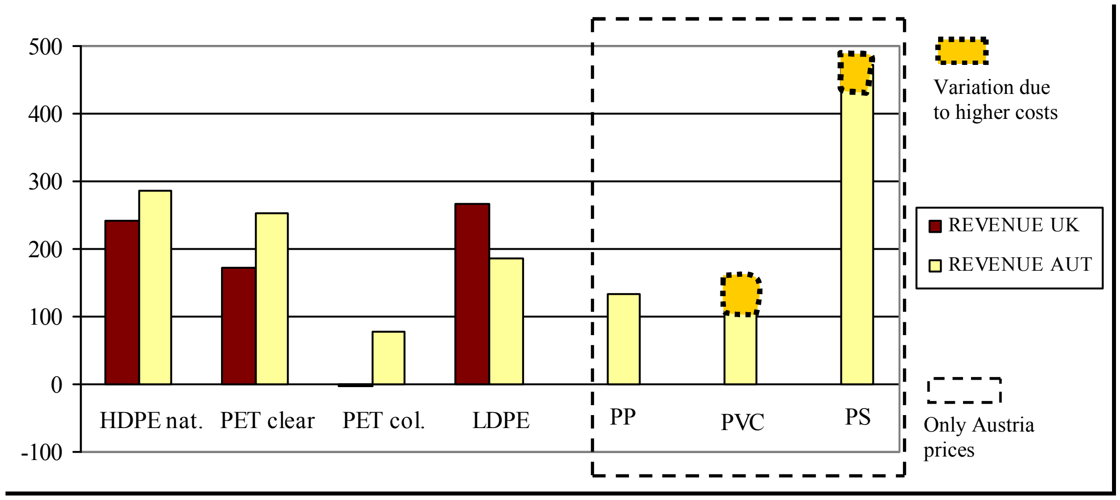

Figure 20: Comparison of recycling between Austria and UK

In Figure 15 the red bars show the revenue of the recycling option in €/tonne for UK, while the yellow show the revenue of the recycling option for Austria.

By comparing recycled PET and HDPE between Austria and UK, it can be noted that recycling is more economical in Austria, resulting in a revenue of about € 250/tonne of recycled HDPE and PET clear. In UK, the value of these plastic types is for about 10% lower. In the case of LDPE, on the contrary, recycling is more economical in the UK. However, this figure has to be treated with caution as the used value of LDPE refers to an approximate data of clear and printed foils. According to the quality of recycled LDPE, the value might differ.

Amongst PP, PVC and PS in Austria, the latter is the plastic type with the highest recycling value. However, the value of PS and PVC refers to recycled grounded plastic instead of baled plastic. Therefore, additional treatment costs arise which lowers the revenue (indicated by the dark-yellow squares. This means that PS probably is followed by PP and finally by PVC in terms of the recycling value.

4.8.4 Economical performance of energy recovery: comparison between UK and Austria

The economical performance of energy recovery in a CHP plant, an EfW plant with electricity production or a gasifier are calculated by subtracting the operational costs of the specific power plants from the income of electricity and or heat sale by taking into account the plant-efficiency.

The following Figures show the energy recovery performance by comparing UK and Austria.

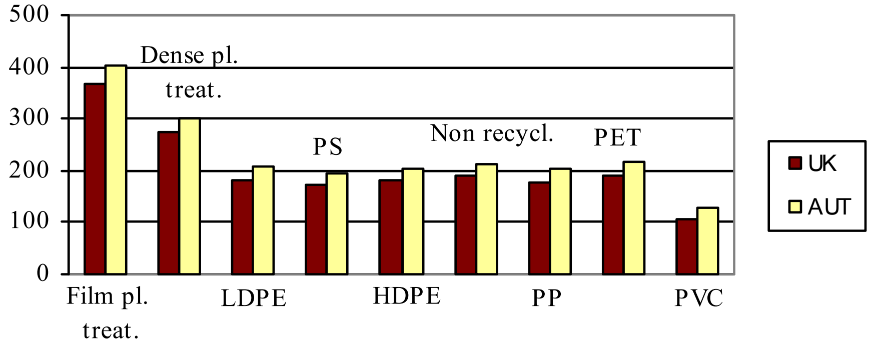

Figure 21: Comparison of energy recovery in a CHP plant between Austria and UK

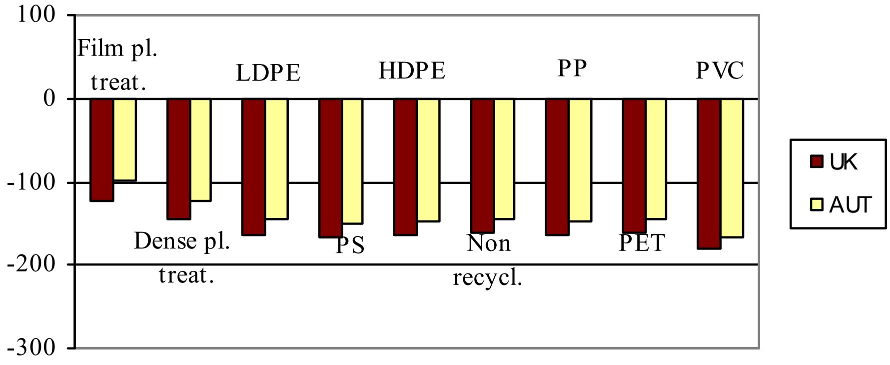

Figure 22: Comparison of energy recovery in an EfW plant with electricity production between Austria and UK

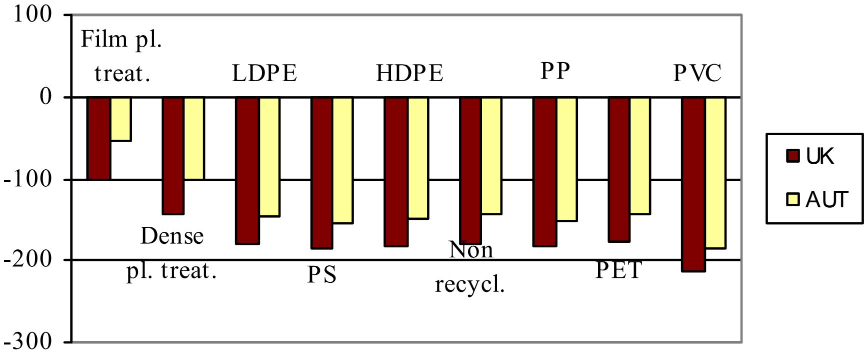

Figure 23: Comparison of energy recovery in a gasifier between Austria and UK

The energy recovery option in Austria performs slightly better than in UK. This is because of the higher electricity wholesale price in Austria.

5 Conclusion

With regard to the specific aims of the present study the following conclusions can be drawn:

- The UK plastic arising in C&I waste has been investigated by actual local surveys and site visits and its percentage seemed to agree with primary and secondary data. There is a high plastic percentage of more than 20% in the mixed C&I waste fraction and more plastic waste produced by these sectors as compared to households. Thus, there is a high potential for processing plastics from C&I waste, either by recycling or by energy recovery. The proportion of C&I plastic waste in Austria seems to be similar to the UK proportion. However, only separately collected plastic waste is recorded whereas the plastic waste in the mixed fraction can just be assumed. In UK, plastic waste from commerce and industries is not recorded as a separate waste stream due to a missing separate collection. Plastics are mixed with other waste fractions.
- Through manual sorting at the waste sites different plastic types were identified. Film plastic represents the biggest fraction with around 40%, followed by dense non recyclable plastics, HDPE and PVC lying in the range between 10 and 20%. PET appears to 8% and PP to about 5%. The arising of PS and Polycarbonate is negligible. In terms of the plastic availability it must be concluded that the contamination of the plastics by other waste fractions like organics as well as dust and sand is high, which diminishes the suitability for recycling. More site visits should be conducted in order to understand the variability of the C&I plastic waste between different locations as well as over time.
- The chemical testing of the different plastic types revealed a high calorific value for all types and fractions due to a high content of hydrocarbons. The proximate analysis showed a high percentage of volatile matter, while the content of fixed carbon is accordingly low. However, the results do not entirely compare to testing of other studies and therefore it is recommended that further chemical

testing is carried out to more fully evaluate the chemical composition of the various plastic types, having an influence on both the energy recovery potential and environmental performance. Emissions of toxic substances during thermal conversion should also be measured for a deeper understanding of the environmental suitability.

- The currently mostly applied and most potential energy recovery and recycling technologies suitable for the treatment of plastic wastes have been identified; they are for the energy recovery option:
  - Conventional incineration with electricity production
  - Incineration with combined heat and power
  - Advanced thermal treatment by gasification

  For the recycling option different separation techniques have been investigated. The techniques of further recycling processing either by feedstock or mechanical recycling were not investigated as this is assumed to be conducted by manufacturing processors rather than by waste management companies. The investigated separation techniques are:
  - Near Infrared separator
  - Density separator
  - Manual separation

  Furthermore, current market availabilities for recycled plastics as well as the market potential for thermal conversion of plastic waste have been identified. While conventional incineration meets criticism and rejection by the public, advanced thermal treatments may benefit from a less negative public perception and its future potential is considered to be high. However, from an economic point of view, incineration with CHP performs currently better than ATT.

  The UK market for recycled plastic waste is still in its infancy. It is supposed to grow and the upward trend is already apparent from the new plastic reprocessing facilities built in the last two years in the UK.

The Austrian market for recycled plastic, on the contrary, is more developed and facilities are not even working at full capacity due to lacking material or material with low quality.

- By comparing the energy recovery options vs. recycling, it can be concluded that incineration with CHP performs generally best. Incineration with CHP scores economically better than recycling for almost all plastic types in both, Austria and UK. HDPE natural with a market value of € 450/tonne in Austria and € 405/tonne in UK is the only plastic type which, in both countries, is more economical when recycled. In Austria, PET clear also performs economically better when recycled; the difference accounting for about € 35/tonne. In UK, also LDPE scores better when recycled rather than incinerated in a CHP plant. LDPE has a market value of € 430/tonne in UK and € 350/tonne in Austria. In the case of PET clear, energy recovery is only slightly better than recycling whereas dense, non recyclable plastics, PP and PET coloured are much more economical when incinerated.

  However, if recycling is compared to incineration with electricity production only, recycling is much more economic. This is due to the low plant efficiency of incinerators of only 20%, while CHP nowadays reaches 80% plant efficiency. Gasification also performs economically worse than recycling, resulting from both, a medium plant efficiency of 40% and currently comparatively high operation costs.

The outcome of this study could be adapted to examine in detail the suitability of the examined mixed C&I waste to be recycled into the different waste types and into the different plastic types. Considering the heterogeneity of the investigated waste in the UK, a sophisticated MRF would be required. Trials about the separability should be undertaken in order to assess the suitability for recycling. These trials might reveal that a more source segregated scheme like in Austria would be more feasible for recycling rather than a very sophisticated and cost-intensive MRF with a high contamination rate.

Finally, it can be concluded, that for most plastic types energy recovery in a CHP plant represents the economically favourable option if compared to recycling. However, if recycling is compared to energy recovery in a conventional incinerator with electricity production or in a gasification plant, recycling is more economic. Moreover, it is likely that the market for recycled plastic will increase in future due to rising crude oil prices. This would result in a higher value for recovered plastic and would make recycling more attractive.

Therefore, if the same study would be conducted in a few years, the outcome could favour recycling rather than energy recovery in a CHP plant.

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