Report on assessment of relevant recycling technologies
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September 2013.

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1. INTRODUCTION
This report is a part of the external assistance on the EU LIFE+ project Plastic Zero, Public Private Cooperations for avoiding plastics as waste, LIFE10 ENV/DK/000098. The report describes the most commonly used sorting technologies and application options for recycled plastic under present market conditions in Europe. The connection between input material (bottles, source separated, residual waste), technology choice, quality of the secondary plastic material and the application options of the material are described and to a certain extent quantified.

Other relevant issues, such as barriers for application, costs and revenues as well as environmental issues are briefly touched upon.

2. THE VALUE CHAIN FOR PLASTIC WASTE
From a systematic point of view the plastic recycling value chain can be divided into the following overall operations: Collection, Sorting/separation, reprocessing (secondary raw material production) and product manufacturing\(^1\).

The different steps of the chain affect each other. The characteristics (composition, type and quality) of the collected plastic will affect the choice of sorting technology, which again affect the quality of the output and what applications the secondary plastic can be used for.

The collected waste may be either pre-consumer waste (scrap from manufacturing of products) or post-consumer waste (waste arising after the use of plastic products at the consumer market). The further steps in processing of the waste will depend largely on the origin and composition of the waste. Often pre-consumer waste will have been subject to a monomaterial collection and it will have low levels of impurities while post-consumer waste usually needs more intensive treatment.

Due to the high quality of the pre-consumer plastic waste it is often economically feasible to recycle these waste streams and this is often already done either internally in the production facility or through external channels.

The main focus of this catalogue is therefore on post-consumer plastic waste.

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\(^1\) Plastic reprocessing can take place either through mechanical or chemical/feedstock recycling. In this report the focus will be on mechanical recycling.
3. **Collection**

The collection systems are specifically dealt with in details in other parts of the Plastic Zero project. Here, an overall description of the collection system is only used to give an impression of the quality and nature of the collected materials.

PlasticsEurope assessed that approximately 25.1 million tonnes post-consumer plastic ended in the waste stream in Europe in 2011. Of this, approximately 25 % was recycled, 35 % incinerated (with energy recovery) and 40 % disposed at landfills (PlasticsEurope, 2012).

Systems that include collection of post-consumer plastic waste can be roughly divided into three overall categories:

- **Monomaterial collection**: The waste collection is designed in order to obtain only one source separated material fraction such as plastics. The waste collection can include several plastic types together or targeting specific plastic types (e.g. PET bottles, or rigid plastic such as pots, tubs and trays).

- **Multimaterial collection (co-mingled collection)**: The collection is designed to collect several types of source separated recyclable materials such as metals, glass and plastics (dry recyclables).
Mixed MSW collection: The waste originating from this type of collection is often very contaminated and needs intensive further treatment (JRC 2011, p. 39). This stream may include the organic waste.

The monomaterial collection of plastic can be designed very differently. The collection systems can be designed for only one or few polymers (e.g. PET bottles), for plastic types (e.g. rigid or flexible plastic) or plastic in general.

The more plastic types included in the collection scheme, the larger volumes will be collected for potential recycling. However, a broad collection of a large variety of plastic types also requires a more thorough fine sorting afterwards resulting in a larger proportion of rejected material and in some cases a lower quality of the output fraction (secondary plastic).

Collection of dry recyclable materials as co-mingled materials provides a relatively cheap collection of a range of materials, but add some extra sorting steps to the subsequent fine sorting of the waste stream before actual production of secondary raw materials.

The residual waste stream can also be sorted resulting in recovery of an additional amount of recyclable materials. The best results from this sorting will be obtained if the waste stream is dry (i.e. organic waste is collected separately).

4. SORTING AND SEPARATION TECHNOLOGIES
Sorting and separation of the collected plastic have the overall purpose to enable high quality recycling, preferably of single polymers. The sorting and separation technologies are aiming at:

› Reducing the quantity of non-targeted plastic polymers

› Reducing the quantity of non-plastics as

› Other recyclables such as metals or glass

› Oil, soil or other contaminants

› Additives within the plastic matrix

Based on the experience from Christensen & Fruegaard (2011), JRC (2011) and COWI, some of the most common sorting operations are described below. Many of the technologies will typically be applied in a certain combination depending on the input material and the quality requirement for the output material. Examples of specific plants with their combination of technologies are described in Section 7.

The output from the sorting plants can be single polymer or different mixes of polymer types (single colours or mixed colours).

Below is presented a brief description of major types of separation technologies/equipment covering

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2 The Austrian Consulting Company IUT (Innovative Umwelttechnik) has provided relevant information on technologies for this chapter.
Most European sorting plants consist of a mix of the above mentioned technologies to ensure an economical and efficient sorting of the input material with satisfying output quality. The exact composition of the specific plant should be adjusted according to input material as well as required output quality. The figure below shows a possible composition of a sorting plant receiving plastic waste, either from monomaterial collection, co-mingled collection or as dry residual waste.

Section 7 contains some European examples of sorting plants for plastic waste streams.

**Figure 2**  
Generic composition of an advanced sorting plant for either monomaterial collected plastic, co-mingled materials (e.g. packaging) or dry residual waste.

**Size separation**
Size separation equipment is splitting the incoming waste/recyclable materials according to size of the individual piece of waste/material. Typical types of equipment for this are:

- Drum screen
- Vibrating screen
- Other screens

Below is shown a drum screen and a vibrating screen.
Figure 3  Drum screen

Figure 4  Vibrating screen
Input materials for size separation equipment often is mixed municipal waste but can also be co-mingled recyclable packaging waste. The size separation equipment normally constitutes the first primary sorting after shredding or bag opening. Shredding is not always necessary.

Typically the screen splits up the incoming waste in three fractions:

- Undersize: < 50 mm
- Middle size: 50/300 mm
- Oversize: > 300 mm

Plastics will normally appear in the middle size and oversize fractions. Middle sized 2D\(^3\) and 3D\(^4\) normally will be further sorted in a ballistic separator and maybe also an air classifier. The oversize fraction normally continues into a manual sorting cabin for handpicking of the large 2D plastic films.

Size separation equipment is widely used in sorting facilities to enhance the performance of subsequent equipment installed at the facility.

**Separation according to gravity/density**

Separation of different plastic materials and removal of impurities can be performed by gravity/density sorting with a range of different technologies, which are described in the following.

**Float sink method:** Density sorting with a fluid medium. Different plastic materials can be separated from each other resulting in a purity of up to 98 % for mixed plastics. This technology can also be used to separate plastic from heavier materials.

**Hydrocyclones:** Density sorting based on the centripetal force to fluid resistance. The waste will be fed into the hydrocyclone in a suspension. Lighter fractions will be transported upwards, while more dense particles will end in the bottom of the cyclone. Size reduction is usually done before treatment in hydrocyclones.

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\(^3\) 2-dimentional plastic, mainly foils, plastic bags etc.

\(^4\) 3-dimentional plastic, such as pots, tubs and trays.
Figure 5  Hydrocyclone. An inner vortex carries the lighter fractions upwards, while an outer vortex carries the heavy fraction downwards.

**Air classifier:** Separate according to materials’ falling velocity" in an air stream. The function is to separate in light and heavy parts. Different types of air classifiers are available. The figure below illustrates the type of air classifier typically used for waste sorting plants.

![Typical air classifier](image)

Figure 6  Typical air classifier.

The air classifier is especially well suited for separation of 2D plastics from more heavy materials (3D plastics and other materials/impurities).

**Ballistic separator:** Automatic sorting according to size, density and rigidness. The sorting results in three fractions;

- Light fraction (light and flat parts)
- Heavy fraction (heavy and cubical parts)
- Fine fraction (e.g. less 20 mm)
Figure 7  Ballistic separator

A ballistic separator is in principle a vibrating perforated deck. A small incline in the deck causes heavy materials to fall to the lower level of the deck while lighter materials such as plastic foils are transported upwards. Fine materials fall through the perforated bottom.

Input materials for gravity/density separation often are the middle fraction from size separation equipment. Considering plastic separation this separation equipment is applied to separate the 2D and the 3D plastic materials as well as to separate major none plastic materials. In the ballistic separator 2D plastic will appear in the light fraction (together with other light none cubic paper and cardboard and textiles). This light fraction will need one or two more sorting steps to separate plastic from paper/cardboard. This might be an air classifier.

The 3D plastic materials will appear in the heavy/cube fraction together with other heavy/cube materials (wood, leather, glass, metals). This heavy fraction will need one or two more sorting steps to sort out the plastic. This might e.g. be metal sorting equipment.

Via change of inclination of the separation component, the performance of the separator can be adjusted.
Gravity/density separation equipment is widely used in sorting facilities to enhance the performance of subsequent equipment installed at the facility - especially the NIR Infrared sorting equipment.

**Magnetic and eddy current separation**

This equipment is applied for sorting out magnetic iron and non-ferrous metals (e.g. aluminium).

The magnet is able to separate ferromagnetic parts from non ferromagnetic materials. Stainless steel and other metals will not be separated in such equipment. Technical solutions cover:

› Electromagnetic separators
› Permanent magnetic separators

The equipment is installed in parallel with a feeding conveyor or perpendicular to the feeding conveyor.
Figure 10  Drum magnet (used to separate small sizes ferro parts having limited mass flow and relatively low moisture content)(IUT, 2010)

Figure 11  Eddy Current separator(IUT, 2010)

Figure 12  Eddie Current separator - principle of function(IUT, 2010)

The Eddy Current separator is applied for sorting out non-ferromagnetic metals such as aluminium, copper, magnesium and silver. The separator is not effective for separating zinc, brass and tin as well as high alloyed steels.

The separation efficiencies of metal separators are shown in the table below.
### Table 1  
**Efficiency of metal separators. IUT, 2012**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Material</th>
<th>Separation (% of input)</th>
<th>Output purity from dry residual waste</th>
<th>Output purity from Co-mingled waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet Eddy Current</td>
<td>Ferro-metals</td>
<td>85 - 95%</td>
<td>85 – 90%</td>
<td>90 - 95%</td>
</tr>
<tr>
<td></td>
<td>Non fe-metals</td>
<td>85 – 95%</td>
<td>85 – 92%</td>
<td>85 – 92%</td>
</tr>
</tbody>
</table>

#### Optic sensor separation

Optic sensor separation covers:

- NIR Infrared
- Colour Line camera
- X-Ray Flurosence

The optic sensor equipment separates materials as paper, cardboard, wood, glass, electric scrap, minerals as well as individual plastic polymers (as PE (LDPE, HDPE), PP, PVC, PET, EPS and ABS) and colours. Black items can normally not be separated due to no reflection⁵.

**NIR Infrared:** Automatic optical sorting using Near Infrared Spectroscopy. UV sensors identify the materials via known wave length for each material and air jets subsequently sort them out into different compartments.

The NIR infrared equipment includes:

- An acceleration conveyor
- Illumination and optical sensors (photo diodes)
- Extraction unit with pressurized air

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⁵ Is however at some facilities sorted out as “PO mix”, which is a very low quality recyclable plastic material.
The NIR Infrared separator is typically applied for separation of
- Mixed plastics by polymer type (except those coloured with carbon black)
- Wood and textiles
- Paper, cardboard and packaging
- PVC in RDF

The plastic and paper separation efficiency of NIR Infrared separators are shown in the Table 2.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Material</th>
<th>Separation (% of input)</th>
<th>Output purity from dry residual waste</th>
<th>Output purity form Co-mingled waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIR</td>
<td>3D plastic</td>
<td>80 - 90%</td>
<td>80 - 90%</td>
<td>85 - 92%</td>
</tr>
<tr>
<td>NIR</td>
<td>2D plastic</td>
<td>85 - 92%</td>
<td>80 - 90%</td>
<td>85 - 92%</td>
</tr>
<tr>
<td>NIR</td>
<td>Paper</td>
<td>70 - 90%</td>
<td>75 - 90%</td>
<td>85 - 92%</td>
</tr>
</tbody>
</table>

Typically, each run of NIR sorting can sort for two parameters (output fractions). Sorting into more than 3 streams thus requires more runs or more NIR scanners.

**Colour Line Camera:**
Automatic optical sorting using camera units to identify the colour of materials (in the visible spectrum) via photo recognition. Air jets subsequently sort them out into different compartments.

The Colour Line camera equipment includes:
A vibration feeder
A camera unit
A light source
A reject unit with pressurized air

The Colour Line Camera is normally applied for separation of
- Different colours of plastic items (e.g. bottles, film)
- Electronic scrap
- Glass
- Minerals

The Colour Line Camera is also able to
- Separate magazines from waste paper
- Determine lead content in glass
- Separate bottle caps (3D camera)

Separation of black plastic can be made via colour line camera.

The colour line camera is at present not widely used when sorting mixed waste from households. As can be observed, the Colour Line Camera however has a wide range of applications. Most of these do not concern plastics sorting and other conventional materials in the household waste stream. Since the costs of this technology does not differ from the NIR technology it is expected that this application will increase in the future to improve the separation efficiency as well as the quality of separated materials.

**X-Ray Fluorescence separation (XRF):**
Automatic sensor based sorting using X-ray photons to impact a targeted material and detect electrons movements and subsequent emission of X-rays. Via XRF spectra different materials can be recognised.

The X-Ray Fluorescence separation is applied for separation of
- Different non-ferrous (copper, brass, stainless steel, aluminium, zinc)
- Electronic scrap (printed circuit boards)
- Minerals

The X-Ray Fluorescence separation is at present not widely used when sorting mixed waste from households as this technology is not able to distinguish between polymers. The use is however expected to increase in future in some areas (separating valuable metals from ash and slag and separation precious metals from e.g. electronic scrap), but not for separating plastic waste.

**Manual sorting/quality control**
Manual sorting and quality control is used for different applications. Typical applications are:
- Separating large items as 2D plastic films from other plastics/mixed recyclables. Is applied either as one of the first operations in a central sorting plant or when separating at oversize fraction after drum screen. Positive sorting.
- As negative sorting, removing non-targeted materials from mono-origin waste streams. Non targeted materials can be impurities or non certified types of packaging waste materials (in producer responsibility systems). This action can also be called quality control of output materials for the purpose of achieving sufficient purity.
The capacity executing manual sorting is very much depending on the actual objective (positive/negative sorting) and the accurateness of the sorting as well as the type of material being separated. Sorting e.g. plastic beverage bottles (each bottle weighing 30 g) one person is able to sort out approx. 50 kg/hour. Sorting heavier plastic containers (size 2½-10 liters) one person might separate as much as 200 kg/hour (IUT, 2013).

Occupational health and safety issues are important having manual control and sorting of waste and recyclable materials. It is observed that manual sorting takes place at various places within a sorting plant both as positive and negative sorting. However, the use of manual sorting varies from plant to plant. Mitigation measures for acceptable occupational health and safety widely include the following interventions:

› Effective ventilation of working places
› Use of protective gloves, masks etc.
› Frequent intermissions of manual separation activities
› Exchange of work place
› Frequent medical health check of workforce

The use of NIR infrared separation equipment and other types of sensor based separation equipment has during time replaced much manual separation work. Manual control of quality of mechanical/optically sorted recyclable materials is, however, still widely used to ensure sufficient purity, e.g. between 96 and 99% requirement in Austria – purity depending on type of material (ARA system, 2011).
Rejects from sorting plants
The amount and quality of rejects from sorting plants equipped with highly advanced automated sorting equipment depends among others on:

- Quality of input
- Criteria for outputs
- Technical concept for the sorting plant
- Market for outputs (recyclable materials and other fractions)

Only few information are available on amount and quality of rejects – and such information have to be seen in the local context.

In Austria the sorting facilities separate only/primarily packaging waste materials certified by the ARA system. Non-certified but recyclable plastics and other materials will not be recycled but instead incinerated or landfilled. In one Austrian sorting plant as much as 60% of the input is not recycled. This fraction is instead incinerated.

The situation is different in Germany where the actual recycling of valuable materials is more dependent on the market situation. One sorting plant in Northern Germany generates an amount of reject of 5-15% - the high value in case of poor market for difficult recyclable materials.

5. REPROCESSING
Reprocessing of the plastic material (fine sorting and production of secondary raw material) usually takes place after sorting/separation of mixed waste/plastic streams or directly on industrial plastic residues.

For high quality plastic products the input for secondary raw material production will often be single-material plastic (e.g. PET or PP) with no or little amounts of contaminants and non-targeted plastic materials. For lower quality plastic products the tolerance with respect to impurities is higher.

The output from the reprocessing is the secondary raw materials used for plastic product manufacturing; usually pellets, but can also be flakes or profiles.

It is important to note that, although divided using this systematic approach, sorting and separation processes can also occur during or in between the reprocessing. The following types of equipment/processes can be applied at a typical reprocessing plant:

- Bale opener
- Additional fine sorting (ballistic separator/NIR infrared separator/magnet/eddy-current separator)
- Washing: water, detergents and agitation is used for cleaning the plastic. Include also “hot washing” with NaOH.
- Microfiltration of water extracting e.g. glue
- Size reduction: cutting the plastic into smaller pieces (e.g. 12 mm) using a shredder
- Vacuum reactor to purify for organic contaminants
Extrusion: In an extruder the waste is melted and pressed through a cone, which will produce long strings of plastic.

Screening: After or during extrusion processes the plastic might pass through a screen in order to remove any solid impurity.

Pelletizing: A rotating knife cuts the strings into pellets that often are cooled in water (Christensen & Fruergaard 2011).

Purity of 99.9% is recorded having a maximum of contaminants at a level of 100-200 ppm.

6. PRODUCT MANUFACTURING

Plastic products can be manufactured using as an input virgin material made from crude oil or secondary raw materials recovered from plastic waste. The input is typically in the form of pellets, flakes or profiles depending on the type of product produced (see also figure 1 or JRC 2011 p. 38).

The use of secondary raw materials often substitutes the production of virgin plastic materials. However, in some cases (often low quality plastic products) other materials, e.g. wood, are replaced. This issue is important when assessing the environmental benefits from recycling of plastic.

The product manufacturing generally involves shaping the plastic intermediates through extrusion, moulding or blowing (JRC 2011).

Plastic from households will typically generate secondary raw materials of different qualities. High qualities from positive sorting (NIR) could be PP, HDPE, PET and PS pellets for high quality plastic products. However, very often, there will be an additional residual plastic waste fraction of mixed plastic, which can either be used for energy purpose or for production of low quality products. Table 3 shows examples of products manufactured from household plastic collected in Germany.

Figure 16: Plastic Pellets, a secondary raw material. Source: www.reeds-carpets.co.uk
Table 3. Examples of products manufactured from household plastic. Source: Alba, 2011.

<table>
<thead>
<tr>
<th>Plastic polymer (secondary raw material)</th>
<th>Product type</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>Household articles: Bins, Buckets, boxes, crates, cradles Automobile parts Industrial: Storage solutions, transportation tools.</td>
</tr>
<tr>
<td>HDPE</td>
<td>Construction: Pipes, tubers, sheets, thick films, profiles Cable protection</td>
</tr>
<tr>
<td>PS</td>
<td>Household articles: Coat hangers, transport boxes Construction</td>
</tr>
<tr>
<td>PET</td>
<td>Fibres: Clothing, textiles, fabrics, car components Packaging: Bottles, films</td>
</tr>
<tr>
<td>LDPE</td>
<td>Films, buckets</td>
</tr>
<tr>
<td>Recycled mixed plastic</td>
<td>Palisades, profiles, pallets, poles</td>
</tr>
</tbody>
</table>

Different products require different qualities of plastic with respect to purity (polymer and impurities) and stable composition. As shown in Table 3 e.g. PET can be used for textile production as well as production of bottles, films etc. Bottles are often produced from recycled plastic in a closed bottle to bottle system, since it requires high quality plastic and must fulfil requirements for food packaging. Production of fleece jackets and similar can tolerate more impurities and can thus be produced from PET from more mixed plastic waste streams. The typical trend is that high quality products substitute virgin plastic, while low quality products increasingly substitutes plastic as well as other materials. For palisades profiles, park benches etc. the substituted material will often be wood.

**Barriers for application**

One of the major obstacles for using recycled plastic in high quality products is stability. For a plastic producer, it is very important to have the exact same raw material every time, since the production is very sensitive to even small deviations in e.g. melting point of the raw material. Deviations in the melting point of the raw material can affect the functionality, strength or durability of the product, which is not acceptable for some applications, such as e.g. medical equipment or automobile parts (affecting safety). The use of secondary plastic for these products is therefore very limited. For less sensitive products a very common way to limit this problem is to "dilute" the secondary plastic with virgin plastic, where the composition in stable and fully documented.

The possible presence of hazardous substances in mixed plastic streams also limits the applications of recycled plastic in products such as medical equipment, toys, food packaging (see below) and baby equipment (e.g. nursing bottles).

Impurities, such as organic waste, bacteria etc. constitute mainly a hygienic problem during the collection, storage and sorting and separation of the plastic waste. However, these impurities are seldom affecting the quality of the end product (secondary plastic).

The plastic consumption for production of food packaging is huge and use of recycled plastic for this purpose is therefore attractive. However, a range of requirements from the European food safety (EFSA) legislation must be fulfilled, which may prevent the use of non-food packaging in the production. This is a barrier for using recycled plastic from mixed plastic streams, since no technologies available today can generally separate food packaging from non-food packaging. Only positive sorting of e.g. easily recognisable items, such as milk or PET bottles (or similar), can be separated from a mixed plastic stream by NIR separation. The use of recycled plastic or food packaging is therefore currently limited to single products (e.g. bottles recognised by NIR) or separately collected materials (e.g. bottle to bottle collection of PET bottles). A future development of sensor based recognition techniques might reduce such a
problem and thereby increase the proportion of secondary plastic involved in production of food packaging. The DEXRT (Dual Energy X-Ray Transmission) and the LIBS (Laser Induced Breakdown Spectroscopy) technologies are examples on such enabling separation of e.g. heavy metal contaminants. This development however is not observed being effectuated at the time being due to high costs connected to some of these technologies (Source: Ciprian Cimpan, Syddansk Universitet).

The colour of the secondary raw material can exclude some uses. Recycled plastic often have grey, green or similar colours, which makes is suitable for production of strongly coloured materials, but not clear products. Production of entirely clear products requires a very clean stream of clear plastic only.

For plastic products of lower quality a higher degree of impurities and varying composition can be accepted without compromising the function of the product.

7. Examples
This section describes European examples of sorting plants treating, among other materials, recyclable plastic.

Central sorting facility Graz
As part of the Austrian take back system is established a central sorting facility in Graz. The Austrian waste contractor Saubermacher is contracted to receive packaging waste from the Graz region and separate certified packaging waste materials.

The input to the plant is separated into recyclable plastics, paper/cardboard and a RDF fraction. Individual output fractions (and quality criteria) are shown below:

- Mixed paper
- Cardboard
- HDPE bottles - 95% purity
- PET bottles (white) - 98% purity
- PET bottles (light blue) - 98% purity
- PET bottles (green) - 98% purity
- LDPE film (white) - 95% purity
- RDF fraction (impurities, non certified packaging waste materials)

The size if the RDF fraction/rejected fraction will depend on several parameters, such as technology, input material and system. The technology has a certain capability to separate certain items from a stream as shown in Table 2. This means that a certain percentage of specific items in the stream will be separated. The resulting reject fraction will depend on the quality of the input material. The more impurities and non-targeted items, the larger the rejected fraction will be. The system will also influence the size of the rejected fraction. In the Austrian system only certified packaging must be included and all other materials are therefore discarded, event if it is suitable for recycling. This increases the size of the rejected fraction due to a system issue and not a technical issue.

The plant is equipped with the following components:
- Reception at floor
- Sorting drum screen (50/300 mm)
- Overbandsmagnet
- Air classifier
- Ballistic separator
- NIR Infrared separator
- Manuel quality control/finesorting
- Balepress

The plant capacity is 6.6 - 7.5 tonne/hour making approx. 11,000 tonnes/year per shift.

Information (and photos) on the Graz sorting plant is obtained via visit at the facility February 2011.

*Figure 17 Images from the Graz sorting facility (1)*
Figure 18  Photos from the Graz sorting facility (II)

Figure 19  Photos from the Graz sorting facility (III)
Figure 20 Photos from the Graz sorting facility (IV)

Figure 21 Photos from the Graz sorting facility (V)

PET reprocessing plant Wöllersdorf, Austria
This plant produces secondary PET raw materials.

Figure 22 PET reprocessing plant at Wöllersdorf
The plant receives source separated and fine sorted PET bottles in different colours from central sorting facilities and other suppliers in Austria and the neighbouring countries. The plant manufactures secondary PET raw material as granulate and flakes. The end products are accepted as packaging for food.

The plant is equipped with the following:
- Bale opener/shredder
- Ballistic separator
- Magnet and eddy-current separator
- Manual sorting/quality control
- Washing equipment
- Extruders

The annual production is approx. 30,000 tonnes. Out of this 5% is not recycled being labels, capsules and PET bottles containing liquids (e.g. olive oil), which disturbed the process and reduces the quality of the re-granulate.

The manufactured PET flakes/pellets are accepted in food packaging.

Information and photos on the PET production plant is obtained via visit at the facility February 2011

**Kruschitz PET reprocessing at Völkermarkt**

This plant produces primarily secondary PET raw materials. The plant receives source separated and fine sorted PET bottles in different colours from central sorting facilities and other suppliers. The plant manufactures secondary PET raw material as granulate and flakes.

The plant is equipped with the following:
- Bale opener/shredder
- Ballistic separator
- NIR Infrared separator
- Secondary shredder (12 mm)
- Pre-washing and density sorting (flotation) (to sort out capsules and the like)
- Hot washing (with NaOH) (to sort out labels)
- Microfiltration of water (to clean for glue)
- Vacuum reactor (heating) (to clean for e.g. organic contaminants)
- Possible drying
- Extruders

According to information received the purity of the secondary PET raw materials can reach 99.9% having maximum impurities of 100 - 200 ppm.
The annual production is approx. 20,000 tonnes. Out of this 5% - 10% is not recycled being paper, dust and other impurities: Labels are recycled.

Information on the PET production plant is obtained via visit at the facility October 2012.

**Swerec AB**
Swerec is a Swedish combined sorting and production plant for secondary raw materials.

A central plastic packaging waste sorting and reprocessing plant has been established in Värnamo in the Southern part of Sweden. The plant is operated by the company Swerec AB. It receives plastic packaging wastes from households in Sweden, Norway and Denmark and produces regenerated plastic as PP, HDPE, LDPE, PET, PVC (flakes, granulate).

The plant is equipped with
- Bale opener/shredder
- NIR Infrared separator
- Washing equipment
- Extruders

The regenerated plastic products have different qualities. Some of the plastic is directly used for production of low quality products, while other outputs are pellets sold for industrial uses in e.g. Holland and Sweden. The products are all grey and can be coloured black, green or brown, but not white or clear. Approximately 80% of the input material is recycled (Swerec, 2012).

**8. COSTS AND REVENUES IN PLASTICS RECYCLING**

**Plastic waste streams and collection systems**
Normally, recycling of plastics takes place either:
- from single waste streams in the plastic industry or
- from mixed/multiple waste streams for households and commercial enterprises

In the first case the system for recycling is quite simple since the polymer type is well known and is collected and processed as secondary plastic in a single waste stream. Such plastic waste is generated at industries manufacturing plastic items/products. The value of such plastic waste can be seen in Table 4 below the column "Cuttings from the industry".

In the second case the system for recycling will often include collection of more than one material (or even a mixed waste stream). This can vary from collection of mixed source separated plastics (several polymers) to collection of mixed source separated plastics and other valuable recyclable materials (e.g. paper, cardboard, metal and glass). It can even be collection of mixed household waste (in a dry fraction or a dry-wet fraction). In this case some kind of automatic separation of plastic polymers will always be required.

To assess the costs of plastic recycling, it is necessary to look at this from a system point of view, since the collection of one fraction may influence the rest of the waste system:

- The plastic can either be collected separately or together with other recyclable materials (co-mingled). Collection of more materials is often more cost-effective due to lower collection costs.
- The separately collected plastic is removed from the treatment of the residual waste (incineration or landfiling), thus reducing the amounts for this treatment.
**Costs for fine sorting**
The following estimates for costs of fine sorting can form basis for estimation of sortings costs:

ADEME France (2013):
This report collects information on the treatment costs from all French sorting facilities (mainly facilities for co-mingled materials). Sorting facilities having capacities of 5,000 – 20,000 tonnes/year experience costs of fine sorting in the range of 120 – 200 EUR/ton. The lowest costs obtained for the largest plants. Costs include capital costs and operational costs, but not revenues from sale of materials.

Danish EPA (2013), a report on increased recycling (carried out by COWI:
Sorting facility for co-mingled materials, capacity of 11,000 tonnes/year: 171 EUR/ton.
Sorting facility for co-mingled materials, capacity of 40,000 tonnes/year: 86 EUR/ton.

Based on this cost information a diagram on fine sorting costs for co-mingled materials is prepared and shown below.

![Diagram of sorting plants costs](image_url)

*Figure 24* Rough estimate of sorting costs for facilities with different capacities. The figure builds mainly on sorting plants for co-mingled materials.

A sorting facility receiving only mixed plastic for sorting will normally receive a lower quantity than a sorting facility receiving co-mingled collected plastic, cardboard and metal from households. The proportion of plastic from a specific catchment area is around 1/3 of the total co-mingled quantity. The capacity of the co-mingled sorting facility thereby can be build three times larger – conditioned the same catchment area for the waste/recyclable materials.

**Value of secondary plastics**
The costs for fine sorting in the previous section does not include the value of the secondary plastic material resulting from the treatment.

The table below shows the value of different quality of plastic materials based on different available sources. The table shows that the price of secondary raw materials is very much depending on the quality.

---

6 Co-mingled fraction include in this example cardboard (39%), plastic (35%) and metal (26%).
### Table 4: Value of different qualities of plastic (virgin and secondary raw materials). All values are given in EUR/t.

<table>
<thead>
<tr>
<th>Type of plastic</th>
<th>Virgin granulate (^1)</th>
<th>Highest quality regenerate ((\text{sec. plastic})^2)</th>
<th>Cuttings from industry (^3)</th>
<th>High quality from source separated and fine sorted plastic ((1, 2 \text{ and } 3, \text{ respectively}))</th>
<th>Source separated mixed plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>1450</td>
<td>600-800</td>
<td>725-1130</td>
<td>280-320</td>
<td>250-350</td>
</tr>
<tr>
<td>LDPE</td>
<td>1500</td>
<td>740-1170</td>
<td>255-295</td>
<td>375</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>1600</td>
<td>600-800</td>
<td>790-1250</td>
<td>15-270</td>
<td>250-350</td>
</tr>
<tr>
<td>PA</td>
<td>2100-3000</td>
<td>??</td>
<td>??</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td>1700</td>
<td>??</td>
<td>870-1355</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>1755</td>
<td>900-1000 ((\text{flakes}))</td>
<td>??</td>
<td>400-600 ((\text{white}))</td>
<td>270</td>
</tr>
<tr>
<td>PET</td>
<td>??</td>
<td>1200 ((\text{pellets}))</td>
<td>??</td>
<td>300-500 ((\text{blue}))</td>
<td></td>
</tr>
<tr>
<td>ABS</td>
<td>2200-2600</td>
<td>805-1610</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed source sep.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-50--25</td>
</tr>
</tbody>
</table>


### Cost example (plastic from households)

The costs of introducing collection of recyclable materials, including plastic, depend entirely on the system chosen. Throughout Europe different systems have been implemented to recycle the valuable materials in the household waste (and in the C&I waste). Some of these are described earlier in this report. The systems differ from each other, often due to local circumstances. Most often the systems integrate recycling of a number of valuable materials within the same “umbrella” (co-mingled materials). It is therefore not an easy task to identify the costs related to recycling of each of the individual materials.

To identify the costs connected to plastics recycling, we have in stead collected general avilable information on the most important cost elements and prepared rough costs estimates covering collection and sorting of collection of plastic (mixed from households) as source-separated and co-mingled, respectively.

**Variant 1 – recycling of mixed source separated plastics from households.**

This include the following operations from collection until a fine sorted polymer is delivered to a plastic recycling industry.

- Collection of the mixed source separated plastic as a single fraction.
- The collection from single family housing is assumed to be in a 4-compartment bin containing plastic, metal, paper and cardboard.
- From multistorey housing the plastic is collected in mini-containers (660 liters) for plastic only.
- Transport to centrally situated facility for fine sorting of the mixed plastic polymers.
- Fine sorting at central facility
- Transport to recycling industry (upgrading the waste polymers to secondary plastic)
**Variant 2 - recycling of mixed source separated plastics together with other recyclable materials (paper, cardboard, metal and glass) from households.**

This include the following operations from collection until a fine sorted polymer is delivered to a plastic recycling industry.

- Collection of the mixed source separated plastic together with other recyclable materials (metal, paper and cardboard) as multiple/co-mingled fractions.
- The collection from single family housing is assumed to be in bins with 2 compartments, hereof one for co-mingled plastics, metals and cardboard.
- From multistorey housing the plastic is collected in mini-containers (660 liters) together with metal and cardboard.
- Transport to centrally situated facility for fine sorting of the co-mingled fractions into individual materials/polymers
- Fine sorting at central facility
- Transport to recycling industry (upgrading the waste polymers to secondary plastic)

The difference between the above two variants is mainly the way the plastic is collected (single or co-mingled). The overall technical concept for the central fine sorting plant, however, is not assumed to differ significantly between the two variants. Fine sorting of mixed source separated plastic as a single waste stream does not in a narrow sense require pre-separation of e.g. metals, glass and cardboard. It is, however, in both variants important to separate impurities from the high value recyclable fraction to ensure a sufficient high quality of the individual recyclable material. In practice, the technical concept for the finesorting plant will be very similar in the two variants, possibly having the required capacity as the only significant difference.

**Collection and transport**

Table 5 shows the data used for calculation of economic costs of collection and transport in the two systems.

**Table 5**  
Datas for calculation of economic costs for two different systems for plastic collection and transport.

<table>
<thead>
<tr>
<th>The collection costs are estimated as shown below:</th>
<th>Bin</th>
<th>Materials</th>
<th>Collections per year</th>
<th>Collection costs (EUR/household)</th>
<th>Collection costs (EUR/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single family</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Var. 1</td>
<td>4 comp., 370 litre</td>
<td>Paper, plastic, metal, cardboard 280 kg/year</td>
<td>12</td>
<td>40</td>
<td>145</td>
</tr>
<tr>
<td>Var. 2</td>
<td>2 comp., 240 litre</td>
<td>Paper, plastic, metal, cardboard 280 kg/year</td>
<td>12</td>
<td>24</td>
<td>86</td>
</tr>
<tr>
<td>Multi family</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Var. 1</td>
<td>Mini container, 660 litre</td>
<td>Plastic</td>
<td></td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Var. 2</td>
<td>Mini container, 660 litre</td>
<td>Plastic, cardboard, metal</td>
<td></td>
<td>73</td>
<td></td>
</tr>
</tbody>
</table>

After collection the plastic waste is to be transported to a sorting facility for fine sorting into individual materials/polymers (including sepapartion of contaminants from the plastic). A transport distance of 100 km might be realistic. The costs of this transport can roughly be estimated at 15 €/ton.

**Fine sorting and transport to recycling industry**

Based on the presented cost estimations for fine sorting the following examples of fine sorting cost can be applied in this overall cost calculation:
Sorting costs for plant for mixed plastic sorting – capacity 20,000 tonnes/year: approx. 120 EUR/ton plastic.

Sorting costs for plant for co-mingled materials including plastic – capacity 60,000 tonnes/year: approx. 80 EUR/ton of recyclable material. It is not possible to estimate a specific sorting cost for plastic, since the treatment of the different materials is integrated at the facility. The treatment cost is therefore an average cost per ton of material treated at the facility.

The capacity of 20,000 tonnes/year is assumed to be a medium sorting plant for mixed plastic sorting. The capacity of the sorting plant for co-mingled materials is assumed to be approximately three times as large (same catchment area), which is a large plant according the sources used (largest facilities mentioned in ADME (2013) is 40,000 t/yr).

After fine sorting the plastic polymers is to be transported to a reprocessing facility producing secondary plastic (as flakes or granulate). A transport distance of 300 km might be realistic. The costs of this transport can roughly be estimated at 20 EUR/ton.

**Total costs for collection, transport and sorting**
Based on the above estimations the total system costs of plastic recycling can be calculated for the two variants for recycling of plastic from households.

*Table 6: Total costs for the two systems for collection, transport and sorting of plastic for recycling.*  
The value of the secondary material is not included.

<table>
<thead>
<tr>
<th>Costs in Euro per ton plastic</th>
<th>Variant 1 – Mixed plastic</th>
<th>Variant 2 – Co-mingled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single family</td>
<td>Multistorey</td>
</tr>
<tr>
<td>Collection</td>
<td>145</td>
<td>79</td>
</tr>
<tr>
<td>Transport 1</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Fine sorting</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Transport 2</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>300</td>
<td>234</td>
</tr>
</tbody>
</table>

The lower costs for Variant 2 (co-mingled) for single family households is mainly due to lower collection costs. For multi-storey households, the difference in collection costs is much less important. Due to the difference in capacity of the sorting facilities included in the calculations, the treatment costs differ between the two variants (120 EUR/ton plastic and 80 kr./average ton recyclable material, respectively).

It is important to note that the above presented estimations are very uncertain and is based on few actual experienced costs – especially in relation to collection but in fact also in relation to actual mixed plastic waste fine sorting. It is further important to note that other pre-conditions for calculation of the collection costs might result in quite some different costs compared to the above presented.

The cost calculations in the table above does not include the value of secondary plastic materials from the fine sorting. The value of different qualities of secondary plastics are shown in Table 4.
9. **ENVIRONMENTAL ISSUES**

Plastic recycling in general is regarded as an environmental advantage compared to the alternatives, which will typically be incineration or landfilling. However, since plastic is a good (fossil) fuel, the recycling system should be effective to ensure the environmental advantage of the recycling.

The following issues are important to the overall environmental performance of the recycling system for plastic:

› The fraction of the collected plastic rejected in the sorting process, e.g. black plastic, non-certified packaging, non-targeted polymers etc.

› Substitution of virgin material (virgin plastic, wood or other materials).

› Energy consumption of the sorting plant

› Transportation distances (especially if the plastic is exported to Asia)

› Alternative waste treatment (incineration or landfilling and the performance of these treatment technologies)

A more specific environmental assessment cannot be performed before an actual system is specified and specific scenarios for comparison are defined. However, below are listed some examples of relevant CO₂ data for estimating the savings obtained by recycling of plastic. CO₂ is here chosen as an example of an environmental impact parameter. A range of other parameters (acidification, smog formation, toxic impacts etc.) could be relevant as well and therefore should be taken into account, but are not shown here.

Positive numbers represent emissions, while negative numbers represent savings due to saved production of e.g. energy or new materials.

The actual savings in a specific case should be assessed in waste system scenarios (collection, treatment and disposal including up-stream and down-stream effects) comparing recycling to the alternative waste treatment option.

**Table 7 CO₂ emissions from transport of plastic**

<table>
<thead>
<tr>
<th>Transportation</th>
<th>Kg CO₂/km/ton</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck, compacting</td>
<td>0.37</td>
<td>EASEWASTE</td>
</tr>
<tr>
<td>Truck (10 t)</td>
<td>0.19</td>
<td>EASEWASTE</td>
</tr>
<tr>
<td>Truck (25 t)</td>
<td>0.09</td>
<td>EASEWASTE</td>
</tr>
<tr>
<td>Ship (40,000 t)</td>
<td>0.02</td>
<td>EASEWASTE</td>
</tr>
<tr>
<td>Ship (150,000 t)</td>
<td>0.002</td>
<td>EASEWASTE</td>
</tr>
</tbody>
</table>

The above given CO₂ numbers are indicative for the magnitude of CO₂ emissions from different transportation options, but may vary considerably depending on the specific choice of vehicle or ship.

Similarly, the CO₂ savings from recycling of plastic given below should only be seen as examples, since the actual savings may vary considerably depending on the specific recycling technology and application chosen.

The total savings/emissions from incineration of plastic depends on the specific situation for the specific incineration plant concerning energy utilisation. Since plastic is based on fossil
material, the incineration of plastic will result in a certain emission of fossil CO₂, which is counted as a netto emission. Only if the produced energy is utilised effectively for electricity and/or heating substituting fossil energy sources, environmental savings may be obtained in a magnitude which makes the overall CO₂ accounting for incinerating plastic a netto CO₂ saving. The CO₂ accounting for incineration of plastic is thus very depending on (1) the efficiency of the incineration plant and (2) the substituted energy sources (electricity and district heating).

<table>
<thead>
<tr>
<th>Source /collection</th>
<th>Treatment</th>
<th>Quality</th>
<th>Application option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households Closed loop (bottle to bottle)</td>
<td>Fine sorting, washing/hot washing (NaOH), vacuum reactor</td>
<td>Highest</td>
<td>Drink bottles (often PET)</td>
</tr>
<tr>
<td>Households Mixed plastic Source separation of mixed plastics (mono-origin or co-mingled)</td>
<td>Positive sorting from stream (NIR), quality control, fine sorting, washing/hot washing (NaOH), vacuum reactor</td>
<td>Highest (up to 99,9% purity)</td>
<td>Food packaging, e.g. HDPE milk bottles</td>
</tr>
<tr>
<td>Households Mixed plastic Source separation of mixed plastics (mono-origin or co-mingled)</td>
<td>Positive sorting from stream (NIR), quality control, fine sorting, washing</td>
<td>Highest (up to 98% purity)</td>
<td>High quality products with high performance criteria</td>
</tr>
<tr>
<td>Households Mixed plastic Source separation of mixed plastics (mono-origin or co-mingled)</td>
<td>NIR sorting, Fine sorting, washing.</td>
<td>85-92 % purity.</td>
<td>Relatively high quality products with lower performance criteria</td>
</tr>
<tr>
<td>Households Mixed dry residual waste</td>
<td>NIR sorting, Fine sorting, washing</td>
<td>80-90 % purity</td>
<td>Products with lower performance criteria</td>
</tr>
<tr>
<td>Residual mixed plastic streams from sorting plants</td>
<td>Low quality</td>
<td>Low quality products</td>
<td></td>
</tr>
</tbody>
</table>
The issue is very complicated with almost unlimited possibilities for variations. E.g. the sorting plant can use different components and run NIR separation several times to improve the results. However, the table is based on the "general findings" for NIR-based sorting plants (including other technical components as well). NIR has been included in most of the described combinations, since the technology is very dominating at the European sorting plants and the trend is to use this technology more and more.

The table shows that the highest quality of secondary raw materials can be obtained either by relatively narrow collection systems (e.g. bottle to bottle collection) or by positive sorting (NIR) from the mixed stream of source separated materials (mono-origin or co-mingled). If the input is source separated materials, it is possible to generate secondary raw materials of very high quality provided efficient quality control and efficient "cleaning" of the fine sorted polymers. If the input for sorting is dry residual waste, the output quality often will be slightly lower. It is important to note, that efficient quality control is strictly necessary to obtain the highest purity. Quality control can for the time being be made only manually and might sometimes result in health impact to involved staff unless strict precautions are made.

The mentioned highest quality is documented via an example from Austria receiving PET bottles (and other plastic items/types). The plastic reprocessing facility producing secondary plastic of high quality receives plastic packaging from Austrian sorting plants generating a purity of up to 98% (ARA quality criteria). The plastic reprocessing facility is equipped with additional NIR sorters, washing equipment (NaOH) and in the end a Vacuum Reactor, which can "clean" the regenerate for organic impurities resulting in a purity of 99.9% (according to received information from Kruschitz Plastics & Recycling, Völkermarkt, Austria). Also other types of polymers (PP, PE etc) are further fine sorted, washed and further "cleaned" at dedicated plastic reprocessing facilities.

Often, the sorting plants will have a residual plastic stream, which is a mix of different polymers. This secondary raw material can be used for low quality products with low performance specifications (or as a fuel).
11. REFERENCES


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