**Appendix A**

**Source-segregated waste material recycling life cycle inventory**

## Introduction

This appendix provides details of the data used and assumptions made to model the source-segregated waste material recycling systems and processes. For each waste material, the following is provided:

* A description of the material composition used in the modelling, including details of the waste material characteristic data used;
* A description of the material recycling system that has been modelled and of the processes within that system;
* A description of the process modelling approach, including details of assumptions taken;
* Details of energy and material inputs and outputs and environmental exchanges (emissions) related to material recycling and/or re-use system processes (i.e. life cycle inventory data);
* An overview of data sources used; and
* Details of market substitution (avoided primary production) resulting from recycling activities.

## Glass

### Summary

An overview of key technical parameters used to model waste glass recycling is presented in Table A1.

**Table A1**

Summary of glass recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Material component | Secondary product | Substituted primary product | Material quality loss (%) |
| Green glass | 6.1 | - | Secondary container glass | Primary container glass | 0 |
| Brown glass | 6.1 | - | Secondary container glass | Primary container glass | 0 |
| Clear glass | 6.1 | - | Secondary container glass | Primary container glass | 0 |
| Mixed glass | 6.1 | - | Secondary container glass | Primary container glass | 0 |

### Green glass

Recycling of green glass was modelled using “mixed glass” recycling as a proxy (see Section 2.5 for details).

### Brown glass

Recycling of brown glass was modelled using “mixed glass” recycling as a proxy (see Section 2.5 for details).

### Clear glass

Recycling of clear glass was modelled using “mixed glass” recycling as a proxy (see Section 2.5 for details).

### Mixed glass

#### Material composition

The material composition of mixed glass used in this study is presented in Table A2.

**Table A2.**

Material composition of mixed paper & card.

|  |  |
| --- | --- |
| Material type | Composition (%) |
| Green glass | 36 |
| Brown glass | 28 |
| Clear glass | 9 |
| Other glass  | 27 |

Source: based on the England, 2010/11 kerbside recycling, household waste recycling centre (HWRC) recycling, and bring site recycling streams compositional estimates for the packaging glass primary level category as presented by Bridgwater (2013).

#### Recycling system description

Mixed glass is sent to a glass manufacturing plant for remelting via a waste glass material recovery facility (MRF). At the MRF, the glass is sorted and crushed to produce glass cullet, which is then transported to a remelting plant for use in the production of secondary glass.

##### Sorting

The process for sorting mixed glass was modelled based on average data from two European glass sorting sites collected between 1994 and 1998 (Hischier, 2007). At the facility, the mixed glass is mechanically crushed and sorted, with the sorted glass cullet contained prior to transportation to a glass manufacturing plant and contaminants removed for disposal. A 6% material loss was assumed during sorting (Hischier, 2007). Inventory data for sorting of waste mixed glass are detailed in Table A3.

**Table A3.**

Inventory data for sorting and preparing of one tonne of waste glass to produce glass cullet.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 3.4 |
| Lubricant | kg | 0.00093 |
| Transport, lorry | tkm | 14 |
| Water | kg | 232 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficients |  |  |
| Glass to remelting | t t-1 | 0.94 |
| Glass to rejects | t t-1 | 0.06 |
| Contaminants to rejects | t t-1 | 1 |
|  |  |  |
| Outputs |  |  |
| Wastewater, to treatment | kg | 0.5 |

Source: adapted from Hischier (2007).

##### Remelting of secondary glass cullets

The process for remelting of glass cullet at a glass manufacturing plant was modelled based on average data from European glass manufacturing plants as reported by Enviros Consulting Ltd (2003), Hischier (2007), and Larsen *et al.* (2009). At the manufacturing plant, the glass cullet is first extensively mechanically and manually sorted to remove contaminants before mixed with typical glass production raw material feedstock, including soda ash (Na2CO3), sand (SiO2), and limestone (CaCO3). The feedstock is then fed in batches into a furnace, which operates at temperatures up to 1,575°C, and molten glass is formed through chemical reactions. Finally, the molten glass is removed from the furnace and sent for forming. Inventory data for remelting of glass cullet in the production of glass are detailed in Table A4. A 0.1% material loss was assumed, based on Enviros Consulting Ltd (2003).

Secondary glass produced from recycled glass cullet was assumed to substitution for primary container glass. No material quality loss was assumed (Edwards and Schelling, 1999; Larsen *et al.*, 2009; Merrild *et al.*, 2012). Primary production data were adapted from several sources (Enviros Consulting Ltd, 2003; Hischier, 2007; Larsen *et al.*, 2009) and are detailed in Table A5. The primary production process includes the quarrying and preparation of raw materials and the melting, forming, cooling, and packaging of primary glass containers.

**Table A4**

Inventory data for remelting of one tonne of glass cullet to produce packaging glass.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |  |  |
| Electricity | kWh | 11.2 |
| Refractory bricks | kg | 8 |
| Water | kg | 1.8 |
| Natural gas | MJ | 2440 |
| Heavy fuel oil | MJ | 1220 |
| Light fuel oil | MJ | 1220 |
|  |  |  |
| Outputs |  |  |
| Packaging glass | kg | 990 |
| Rejects | kg | 10 |
| Wastewater, to treatment | kg | 1.6 |

Source: adapted from Enviros Consulting Ltd (2003), Hischier (2007), and Larsen *et al.* (2009).

**Table A5**

Inventory data for the production of one tonne of glass containers from primary glass.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 2.9 |
| Natural gas | MJ | 2350 |
| Heavy fuel oil | MJ | 1630 |
| Light fuel oil | MJ | 1630 |
| Sand | kg | 730 |
| Limestone | kg | 103 |
| Soda | kg | 193 |
| Water | m3 | 1.8 |
| Refractory brick | kg | 8 |
| Dolomite | kg | 139 |
| Feldspar | kg | 36 |
|  |  |  |
| Outputs |  |  |
| Glass | kg | 1000 |
| Residuals, to disposal | kg | 10 |
| Wastewater, to treatment | kg | 1.6 |
| Emissions to air |  |  |
| Carbon dioxide, fossil | kg | 200 |

Source: adapted from Enviros Consulting Ltd (2003), Hischier (2007), and Larsen *et al.* (2009).

## Paper & card

### Summary

An overview of key technical parameters used to model waste paper and card recycling is presented in Table A6.

**Table A6**

Summary of paper and card recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Paper | 2.7 | Paper | Secondary newsprint | Primary newsprint | 0 |
| Card | 10.1 | Card | Testliner | Kraftliner | 10 |
| Wellenstoff | Semi-chemical fluting | 10 |
| Books | 10.1 | Books | Testliner | Kraftliner | 10 |
| Wellenstoff | Semi-chemical fluting | 10 |
| Mixed paper & card | 10.1 | Mixed paper & card | Testliner | Kraftliner | 10 |
| Wellenstoff | Semi-chemical fluting | 10 |
| Yellow pages | 10.1 | Yellow pages | Testliner | Kraftliner | 10 |
| Wellenstoff | Semi-chemical fluting | 10 |

### Paper

#### Material composition

Paper was assumed to be composed of 100% newspapers.

#### Recycling system description

Collected paper is sent to a paper mill for use in the production of newsprint. At the paper mill, the paper feedstock is shredded and sorted to remove contaminants before being mechanically pulped and bleached. The paper is then deinked to produce deinked pulp (DIP), which is then used in in the production of newsprint. The process for paper recycling was modelled based on average data from several European newsprint producers. Inventory data are presented in Table A7 (Hischier, 2007). A 2.7% material loss during reprocessing was assumed (Hischier, 2007).

Secondary newsprint was assumed to substitute for primary newsprint. No material quality loss was assumed (Merrild *et al.*, 2012). Primary production data were sourced from the ecoinvent v2.2 database (“paper, newsprint, 0% DIP, at plant”) (Hischier, 2007). The process includes the transportation of raw material to the paper mill, mechanical pulping and bleaching, paper production and internal wastewater treatment.

### Card

#### Recycling system description

Card is sent to a paper mill for reprocessing and use in the production of recycled cardboard base papers. The process was modelled based on average data from European paper mills collected between 1995 and 2005 (Hischier, 2007). At the paper mill, the card is first shredded and sorted to remove contaminants (for LCI data, see Table A8). The feedstock is then deinked and used in the production of cardboard base paper (testliner, 58%; wellenstoff, 42%). Inventory data for the use of card in the production of testliner and wellenstoff cardboard base papers are presented in Table A9 and Table A10, respectively.

Recycled base papers used in the manufacturing of cardboard were assumed to substitute for base papers constructed from virgin wood. Cardboard base papers produced from recycled fibres are generally of a lower quality to those constructed of virgin fibres due to a loss in fibre strength suffered as a result of reprocessing (Merrild *et al.*, 2009; Rigamonti *et al.*, 2009; Wang *et al.*, 2012); a 10% material quality loss was assumed based on Merrild *et al.* (2012). It was assumed that testliner and wellenstoff would substitute for primary kraftliner and primary semi-chemical fluting production, respectively. Primary production data were sourced from the ecoinvent v2.2 database (“corrugated board base paper, kraftliner, at plant” and “corrugated board base paper, semichemical fluting, at plant”) (Hischier, 2007). The processes include the transportation and handling of raw material and energy inputs to the paper mill, chemical pulping, paper production, and internal wastewater treatment.

### Books

Books recycling was modelled using the card recycling system, as described in Section 3.3, where all process inventory data used to model card recycling were applied consistently for books.

**Table A7**

Inventory data for sorting of waste paper and its use in the production of newsprint. The function unit of each sub-process is one tonne of waste paper input.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Unit | Quantity |  | Unit | Quantity |
| *Sorting* |
| Inputs |  |  |  |  |  |
| Electricitya | kWh | 40 |  |  |  |
|  |  |  |  |  |  |
| Process parameters |  |  |  |  |  |
| Transfer coefficientsb |  |  |  |  |  |
| Paper to newsprint production | t t-1 | 0.973 |  |  |  |
| Paper to rejects | t t-1 | 0.027 |  |  |  |
| Contaminants to rejects | t t-1 | 1 |  |  |  |
|  |  |  |  |  |  |
| *Newsprint production* |
| Inputs |  |  | Outputs |  |  |
| Wood | m3 | 1.43 | Newsprint | kg | 1320 |
| Sulphite pulp | kg | 23.3 | Wood ash, to disposal | kg | 13.4 |
| Kaolin | kg | 22.2 | Sludge, to disposal | kg | 0.272 |
| Aluminium sulphate | kg | 3.6 | Ash from deinking, to disposal | kg | 58.9 |
| Malusil | kg | 3.4 |
| De-inking emulsion | kg | 0.71 | Emissions to air |  |  |
| Anhydrous sodium dithionite | kg | 3.51 | Carbon dioxide, biogenic | kg | 327 |
| Nitrogen | kg | 0.25 | Carbon dioxide, fossil | kg | 247 |
| Sodium silicate | kg | 22.1 | Methane, biogenic | kg | 0.0014 |
| Sodium hydroxide | kg | 14.4 | Methane, fossil | kg | 0.114 |
| White phosphorus | kg | 0.04 | Dinitrogen monoxide | kg | 0.0101 |
| Sulphur dioxide | kg | 5 |  |  |  |
| Quicklime | kg | 0.4 |  |  |  |
| Bentonite | kg | 0.9 |  |  |  |
| Fatty acids | kg | 4.48 |  |  |  |
| Ethylenediaminetetraacetic acid (EDTA) | kg | 0.89 |  |  |  |
| Diethylene triamine penta-acetic acid (DTPA) | kg | 1.23 |  |  |  |
| Retention acids | kg | 0.17 |  |  |  |
| Organic chemicals  | kg | 2.45 |  |  |  |
| Electricity | kWh | 2130 |  |  |  |
| Hard coal | kg | 3.82 |  |  |  |
| Heavy fuel oil | kg | 13.8 |  |  |  |
| Natural gas | MJ | 274 |  |  |  |
| Lignite briquettes | MJ | 152 |  |  |  |

Source: adapted from Hischier (2007).

aPer tonne of feedstock, 2,130 kWh of electricity is used in the production of newsprint (Hischier, 2007). Total electricity use was allocated to a pre-sorting phase based on the mass of rejected material, where electricity use during pre-sorting of one tonne of feedstock equals total electricity use (2,130 kWh) \* mass of rejected material (19.4 kg), which equals 40 kWh electricity per tonne feedstock. The remaining 2,090 kWh of electricity was allocated to the reprocessing phase.

bTransfer coefficients for the pre-sorting phase were calculated from the Hischier (2007) data set as follows: per tonne of feedstock, a total of 19.4 kg material is rejected (1.9% of input). 13.3% of the rejected material is waste paper (target material), with the remaining reject composed of contaminants. It therefore follows that 98% of the feedstock is waste paper, of which 0.27% is rejected (hence, paper to reject TC of 0.027). 100% of contaminants are rejected (hence, default to reject TC of 1).

**Table A8**

Inventory data for sorting of one tonne of waste card.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |  |  |
| Electricitya | kWh | 4 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficientsb |  |  |
| Card to testliner production | t t-1 | 0.57 |
| Card to wellenstoff production | t t-1 | 0.42 |
| Card to rejects | t t-1 | 0.01 |
| Contaminants to rejects | t t-1 | 1 |

Source: adapted from Hischier (2007).

aPer tonne of feedstock, 97 kWh of electricity is used in the production of testliner and wellenstoff (Hischier, 2007). Total electricity use was allocated to a pre-sorting phase based on the mass of rejected material, where electricity use during pre-sorting of one tonne of feedstock equals total electricity use (97 kWh) \* mass of rejected material (39.3 kg), which equals 4 kWh electricity per tonne feedstock. The remaining 93 kWh of electricity was allocated to the two base paper production processes.

bCard reject rate was calculated based on data from the ecoinvent v2.2 processes "corrugated board base paper, testliner, at plant" and "corrugated board base paper, wellenstoff, at plant" (Hischier, 2007) as follows: 1) per tonne of feedstock, a total of 39 kg material is rejected (3.9%). 19.8% of the rejected material is card, with the remaining reject composed of contaminants. It therefore follows that 96.8% of the feedstock is waste paper, of which 0.8% is rejected (rounded here to 1%). 100% of non-target materials are rejected (hence, default to reject TC of 1); 2) Transfer coefficients for card to the production of either testliner or wellenstoff are based on the proportion of each base paper type used in the production of single wall corrugated board, as detailed in the ecoinvent v2.2 process "corrugated board, recycling fibre, single wall, at plant" (Hischier, 2007), minus material losses.

### Mixed paper & card

#### Material composition

The material composition of mixed paper & card used in this study is presented in Table A11.

**Table A11**

Material composition of mixed paper & card.

|  |  |
| --- | --- |
| Material type | Composition (%) |
| Newspapers | 36 |
| Magazines | 20 |
| Other paper | 20 |
| Cardboard | 24 |

Source: based on the England, 2010/11 kerbside recycling, household waste recycling centre (HWRC) recycling, and bring site recycling streams compositional estimates for the paper and card primary level categories as presented by Bridgwater (2013).

#### Recycling system description

Mixed paper & card recycling was modelled using the card recycling system, as described in Section 3.3, where all process inventory data used to model card recycling were applied consistently for yellow pages.

### Books

Books recycling was modelled using the card recycling system, as described in Section 3.3, where all process inventory data used to model card recycling were applied consistently for books.

### Yellow pages

Yellow pages recycling was modelled using the card recycling system, as described in Section 3.3, where all process inventory data used to model card recycling were applied consistently for yellow pages.

**Table A9**

Inventory data for recycling of one tonne of card in the production of testliner corrugated board base paper.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Unit | Quantity |  | Unit | Quantity |
| Inputs |  |  | Outputs |  |  |
| Water | kg | 120 | Testliner | kg | 950 |
| Aluminium sulphate | kg | 0.73 | Wood ash mixture, to disposal | kg | 3.0 |
| Phosphoric acid | kg | 0.15 |
| Hydrochloric acid | kg | 0.09 | Sludge, to disposal | kg | 1.77 |
| Sodium hydroxide | kg | 0.33 | Ash, to disposal | kg | 0.499 |
| Biocides | kg | 0.09 | Emissions to air |  |  |
| Ethoxylated alcohols | kg | 0.26 | Carbon dioxide, biogenic | kg | 14 |
| Lubricating oil | kg | 0.26 | Carbon dioxide, fossil | kg | 447 |
| Alkyl ketene dimer (AKD) sizer | kg | 0.9 | Methane, fossil | kg | 0.12 |
| Urea (as N) | kg | 0.21 | Nitrous oxide | kg | 0.0013 |
| Potato starch | kg | 31.7 |  |  |  |
| Core board | kg | 23.2 |  |  |  |
| Flat pallet (wood) | unit | 0.00043 |  |  |  |
| PET, granulate | kg | 0.7 |  |  |  |
| HDPE, granulate | kg | 0.02 |  |  |  |
| Cold-rolled steel  | kg | 0.06 |  |  |  |
| Electricity | kWh | 88.2 |  |  |  |
| Heavy fuel oil | kg | 0.03 |  |  |  |
| Light fuel oil | kg | 0.18 |  |  |  |
| Compressed natural gas (CNG) | MJ | 6600 |  |  |  |
| Hard coal | kg | 16 |  |  |  |
| Lignite briquettes | MJ | 340 |  |  |  |

Source: adapted from Hischier (2007).

**Table A10**

Inventory data for recycling of one tonne of card in the production of wellenstoff corrugated board base paper.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Unit | Quantity |  | Unit | Quantity |
| Inputs |  |  | Outputs |  |  |
| Water | kg | 120 | Wellenstoff | kg | 920 |
| Aluminium sulphate | kg | 0.71 | Wood ash mixture, to disposal | kg | 3.0 |
| Sludge, to disposal | kg | 1.73 |
| Phosphoric acid | kg | 0.12 | Ash, to disposal | kg | 0.49 |
| Hydrochloric acid | kg | 0.07 | Emissions to air |  |  |
| Sodium hydroxide | kg | 0.3 | Carbon dioxide, biogenic | kg | 14 |
| Biocides | kg | 0.08 | Carbon dioxide, fossil | kg | 437 |
| Ethoxylated alcohols | kg | 0.2 | Methane, fossil | kg | 0.117 |
| Lubricating oil | kg | 0.25 | Nitrous oxide | kg | 0.00127 |
| Urea (as N) | kg | 0.32 |  |  |  |
| Potato starch | kg | 33.7 |  |  |  |
| Core board | kg | 2.07 |  |  |  |
| Flat pallet (wood) | unit | 0.00042 |  |  |  |
| PET, granulate | kg | 0.05 |  |  |  |
| HDPE, granulate | kg | 0.05 |  |  |  |
| Cold-rolled steel | kg | 0.03 |  |  |  |
| Electricity | kWh | 86.2 |  |  |  |
| Heavy fuel oil | kg | 0.0291 |  |  |  |
| Light fuel oil | kg | 0.175 |  |  |  |
| CNG | MJ | 6500 |  |  |  |
| Hard coal | kg | 15.65 |  |  |  |
| Lignite briquettes | MJ | 330 |  |  |  |

Source: adapted from Hischier (2007).

## Metal

### Summary

An overview of key technical parameters used to model waste metals recycling is presented in Table A12.

**Table A12**

Summary of paper and card recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Steel cans | 13.2 | Steel | Crude steel | Steel | 0 |
| Aluminium cans | 5.1 | Aluminium | Aluminium | Aluminium | 0 |
| Mixed cans | 14.2 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Other scrap metal | 14.2 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Aluminium foil | 5.1 | Aluminium | Aluminium | Aluminium | 0 |
| Aerosols | 14.2 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Fire extinguishers | 17.4 | Steel | Crude steel | Steel | 0 |
| Gas bottles | 17.4 | Steel | Crude steel | Steel | 0 |
| Bicycles | 14.2 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |

### Steel cans

#### Recycling system description

Recovered ferrous scrap is sent to an electric arc furnace (EAF) for direct smelting to produce secondary steel. A range of inventory data for use of scrap steel in the production of liquid steel in state-of-the-art EAFs within the EU is provided by the European Commission Joint Research Centre (Remus *et al.*, 2013). During the process, ferrous scrap is delivered to the EAF plant and deposited at a scrap bay, where it is loaded into large baskets. The baskets containing the ferrous scrap are transported by crane first to a scrap pre-heater and then to the EAF, which is “charged” with the ferrous scrap and limestone. The furnace lid is fastened and graphite electrodes are lowered into the furnace interior, striking an arc between the charged material and the electrodes. The arc is set to bore into the charged material, melting the ferrous scrap. Once the scrap is melted, oxygen is blown into the furnace and burnt lime is added. This oxides and neutralises contrary elements (such as carbon, silicon, and manganese) in the scrap metal; purifying the steel. The oxidised, neutralised elemental impurities form slag, which is poured off the surface and sent for disposal in a landfill. The furnace is then tilted and the molten steel is tapped out into a preheated ladle. Alloys are simultaneously added to the steel during tapping, along with more lime. The crude steel is then ready for use in secondary steelmaking or for casting. Inventory data for the process of direct smelting of ferrous scrap in an EAF is detailed in Table A13. A material loss rate of 13.2% was assumed (Burchart-Korol, 2013). No material quality loss was assumed (World Steel Association, 2011).

Crude steel was assumed to substitute for primary steel. Primary production data were sourced from the ecoinvent v2.2 database (“steel, converter, unalloyed, at plant”) (Classen *et al.*, 2009). The process includes the transportation of metal ores and other input materials to the converter, the primary steel production process, and steel casting.

**Table A13**

Inventory data for direct smelting of one tonne of ferrous scrap in an EAF to produce steel.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 347 |
| Natural gas | m3 | 3.9 |
| Refractory | kg | 49 |
| Quicklime | kg | 37 |
| Electrodes (graphite) | kg | 1.8 |
| Alloysa | kg | 1.9 |
|  |  |  |
| Outputs |  |  |
| Crude steel | kg | 868 |
| Slag, to disposal | kg | 160 |
| Wastewater, to treatment | m3 | 0.45 |
| Refractory waste, to disposal | kg | 6.2 |
| Dust, to disposal | kg | 2.9 |
| Sludge, to disposal | kg | 7.4 |
| Emissions to air |  |  |
| Carbon dioxide, fossil | kg | 224 |
| Nitrous oxide | kg | 0.00083 |

Source: adapted from Burchart-Korol (2013) and Remus *et al.* (2013).

aNot included in this study.

### Aluminium cans

#### Recycling system description

Aluminium scrap is sent for re-melting and casting into secondary aluminium billets via metal merchants and waste management companies, who sort, prepare, and treat the scrap aluminium.

#### Aluminium scrap preparation

The process for sorting and preparing the aluminium scrap was modelled based on average data from European aluminium scrap preparation plants, as detailed by EAA (2008). The aluminium is first recovered through a combination of mechanical shredding, magnetic separation, sink-and-float installations, and eddy current separation, successively. The separated aluminium is then mechanically cleaned, so as to remove coatings, and dried prior to charging. The aluminium scrap is then ready for transportation to a melting plant. A 4.8% material loss was assumed during the sorting and preparation process (EAA, 2008). No material quality loss was assumed. Inventory data for the sorting and preparation of aluminium scrap are detailed in Table A14.

**Table A14**

Inventory data for sorting and preparation of one tonne of aluminium scrap.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 190 |
| Heat, natural gas | MJ | 614.3 |
| Heat, heavy fuel oil | MJ | 81.4 |
| Ferro-silicon | kg | 1.1 |
| Water | kg | 43 |
| Light fuel oil | kg | 0.16 |
| Hydraulic oil (lubricant) | kg | 0.01 |
| Detergent | kg | 0.11 |
| Lime | kg | 0.13 |
| Additives (alloys) | kg | 0.44 |
|  |  |  |
| Outputs |  |  |
| Aluminium scrap, to reprocessor | kg | 952 |
| Oil, to incineration | kg | 1.19 |
| Hazardous waste, to disposal | kg | 6.3 |
| Dirt (inert material), to disposal | kg | 8 |
| Filter dust, to disposal | kg | 3.35 |

Source: adapted from EAA (2008).

#### Secondary aluminium billet production

The process for melting, alloying, and casting of the prepared aluminium scrap was modelled based on average data from European aluminium scrap preparation plants, as detailed by Classen *et al.* (2009). The prepared aluminium scrap is combined with “new” process scrap of known composition in order that precise alloy compositions may be obtained in the final product. The scrap is loaded into a furnace and heated to produce molten aluminium. Aluminium dross, a thin layer of aluminium oxide that is produced as a result of surface oxidation, is skimmed off and removed prior to being recycled into aluminium alloys and aluminium oxides. Post-melting, the molten aluminium is cast into extrusion billets or rolling ingots and are used in the production of aluminium beverage cans. Inventory data for the melting, alloying, and casting of prepared aluminium scrap are detailed in Table A15. A 0.3% material loss was assumed (Classen *et al.*, 2009). No material quality loss was assumed (EAA, 2013b; EAA, 2013a).

Secondary aluminium billets were assumed to be used in the production of beverage cartons where they would substitution for primary aluminium. The primary production data were sourced from the ecoinvent v2.2 database (“aluminium, primary, at plant”) (Classen *et al.*, 2009). The process includes the production and casting of aluminium ingots, the transportation of auxiliary materials to the plant, and the disposal of wastes.

### Mixed cans

Mixed cans recycling was modelled using the other scrap metal recycling system, as described in Section 4.5, where all process inventory data used to model other scrap metal recycling were applied consistently for mixed cans.

**Table A15**

Inventory data for melting, alloying and casting of one tonne of old scrap to secondary aluminium billets.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Water | m3 | 7.73 |
| Chlorine | kg | 1.6 |
| Copper | kg | 0.73 |
| Electricity | kWh | 280 |
| Heat, heavy fuel oil | MJ | 498 |
| Heat, natural gas | MJ | 8030 |
| Light fuel oil | kg | 0.0023 |
| Nitrogen | kg | 1.7 |
| Sodium chloride | kg | 13.3 |
| Silicon | kg | 11.9 |
| Hydrochloric acid | kg | 0.2 |
| Lime | kg | 7.19 |
| Sodium hydroxide | kg | 1.54 |
| Sulphuric acid | kg | 7.73 |
| Zinc | kg | 63 |
|  |  |  |
| Outputs |  |  |
| Secondary aluminium billets | kg | 970 |
| Filter dust, to disposal | kg | 9.35 |
| Hazardous waste, to disposal | kg | 14.1 |
| Inert waste, to disposal | kg | 1.96 |
| Residuals, to disposal | kg | 0.08 |

Source: adapted from Classen *et al.* (2009).

### Other scrap metal

#### Material composition

Other scrap metal was assumed to comprise 42% non-ferrous metal and 58% ferrous metal (based on Bridgwater, 2013).

#### Recycling system description

Waste scrap metal is sent to a scrap metal merchant where the ferrous and non-ferrous components are separated and sent for use in crude steel and aluminium production, respectively.

#### Scrap metal sorting and preparation

The process for sorting and preparing the scrap metal was modelled based on average data from European aluminium scrap preparation plants, as detailed by EAA (2008), which was used as a proxy. The ferrous and non-ferrous metals are first separated and recovered through a combination of mechanical shredding, magnetic separation, sink-and-float installations, and eddy current separation, successively. The separated metals are then cleaned, so as to remove coatings, and dried prior to bailing. The separated scrap metals are then ready for transportation to ferrous and non-ferrous melting plant. A 4.8% material loss was assumed during the sorting and preparation process (EAA, 2008). No material quality loss was assumed. Inventory data for the sorting and preparation of scrap metal are detailed in Table A16.

**Table A16**

Inventory data for sorting and preparation of one tonne of scrap metal.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 190 |
| Heat, natural gas | MJ | 614.3 |
| Heat, heavy fuel oil | MJ | 81.4 |
| Ferro-silicon | kg | 1.1 |
| Water | kg | 43 |
| Light fuel oil | kg | 0.16 |
| Hydraulic oil (lubricant) | kg | 0.01 |
| Detergent | kg | 0.11 |
| Lime | kg | 0.13 |
| Additives (alloys) | kg | 0.44 |
|  |  |  |
| Outputs |  |  |
| Aluminium scrap, to reprocessor | kg | 400 |
| Steel scrap, to EAF  | kg | 550 |
| Scrap metal, to disposal | kg | 50 |
| Oil, to incineration | kg | 1.19 |
| Hazardous waste, to disposal | kg | 6.3 |
| Dirt (inert material), to disposal | kg | 8 |
| Filter dust, to disposal | kg | 3.35 |

Source: adapted from EAA (2008).

#### Metals reprocessing

Recovered steel scrap is sent to an EAF for direct smelting to produce secondary steel. Details of the steel recycling system are outlined in Section 4.2. Recovered aluminium scrap is sent for re-melting and casting into secondary aluminium billets. Details of the aluminium recycling system are outlined in Section 4.3.

### Aluminium foil

Aluminium foil recycling was modelled using the aluminium cans recycling system, as described in Section 4.3, where all process inventory data used to model aluminium cans recycling were applied consistently for aluminium foil.

### Aerosols

Aerosols recycling was modelled using the mixed cans recycling system, as described in Section 4.4, where all process inventory data used to model mixed cans recycling were applied consistently for aerosols.

### Fire extinguishers

Fire extinguishers recycling was modelled using the gas bottles recycling system, as described in Section 4.9, where all process inventory data used to model gas bottles recycling were applied consistently for fire extinguishers.

### Gas bottles

#### Material composition

The composition of used gas bottles is highly variable due to the variety of different gaseous product that they may contain. Due to a lack of specific information, it was assumed that gas bottles are composed wholly of steel and are empty of their gaseous product at the point of disposal.

#### Recycling system description

Upon collection, gas bottles are sent to a scrap metal merchant. The process for sorting and preparing the waste mixed cans was modelled based on average data from European aluminium scrap preparation plants, as detailed by EAA (2008), which was used as a proxy. A description of the process is provided in Section 4.3.2. A 4.8% material loss was assumed during the sorting and preparation process (EAA, 2008). Inventory data for the sorting and preparation of used gas bottles are detailed in Table A17. Sorted gas bottles are then sent for smelting in an EAF to produce crude steel. Details of the steel recycling system are provided in Section 4.2.

### Bicycles

Due to a lack of specific data, bicycles recycling was modelled using the mixed cans recycling system, as described in Section 4.4, where all process inventory data used to model mixed cans recycling were applied consistently for bicycles.

**Table A17**

Inventory data for sorting and preparation of one tonne of mixed cans.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 190 |
| Heat, natural gas | MJ | 614.3 |
| Heat, heavy fuel oil | MJ | 81.4 |
| Ferro-silicon | kg | 1.1 |
| Water | kg | 43 |
| Light fuel oil | kg | 0.16 |
| Hydraulic oil (lubricant) | kg | 0.01 |
| Detergent | kg | 0.11 |
| Lime | kg | 0.13 |
| Additives (alloys) | kg | 0.44 |
|  |  |  |
| Outputs |  |  |
| Steel scrap, to EAF | kg | 952 |
| Steel, to rejects | kg | 48 |
| Oil, to incineration | kg | 1.19 |
| Hazardous waste, to disposal | kg | 6.3 |
| Dirt (inert material), to disposal | kg | 8 |
| Filter dust, to disposal | kg | 3.35 |

Source: adapted from EAA (2008).

## Plastic

### Summary

An overview of key technical parameters used to model waste plastics recycling is presented in Table A18.

**Table A18**

Summary of plastics recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Mixed plastics | 30.4 | PET | PET flakes | PET flakes | 10 |
| HDPE | HDPE granulate | HDPE granulate | 10 |
| PVC | PVC pellets | PVC pellets | 10 |
| PP | PP granulate | PP granulate | 10 |
| Mixed plastic bottles | 31.3 | PET | PET flakes | PET flakes | 10 |
| HDPE | HDPE granulate | HDPE granulate | 10 |
| PVC | PVC pellets | PVC pellets | 10 |
| PP | PP granulate | PP granulate | 10 |
| PET | 5 | PET | PET flakes | PET flakes | 10 |
| HDPE | 12 | HDPE | HDPE granulate | HDPE granulate | 10 |
| PVC | 12 | PVC | PVC pellets | PVC pellets | 10 |
| LDPE | 47 | LDPE | LDPE pellets | LDPE pellets | 10 |
| PP | 12 | PP | PP granulate | PP granulate | 10 |

### Polymer types

Waste plastics arise in a range of formats (e.g. bottles, packaging, and caps) and may be composed of various plastic polymer types – seven categories of plastic polymer are defined by the Society of the Plastics Industry (SPI) in their Resin Identification Code (RIC) system (see Table A19). The mixed plastics recycling industry is interested in recovering those waste plastic polymer types that are readily recyclable and for which markets exist for their post-reprocessing products (i.e. plastic pellets/granulate). Due to strong market demand, of foremost interest to the industry is the recovery and recycling of plastics composed of PET and HPDE polymers (WRAP, 2010b). However, as local authorities in the UK endeavour to meet increasingly ambitious recycling targets, the recovery and recycling of other polymers is becoming more common (WRAP, 2006).

**Table A19**

Types of plastic by RIC, their common household uses, and their recycling statuses in the UK.

| RIC code | Polymer name | Common household uses | Recycling status |
| --- | --- | --- | --- |
| Plastic-recyc-01.svg | Polyethylene terephthalate (PET) | Beverage bottles, medicine jars, carpet fibre, polyester fibres, and tote bags | Commonly recycled |
|  | High-density polyethylene (HDPE) | Containers (milk, motor oil, shampoo, soap, bleaches, detergents, etc.) | Commonly recycled |
| Plastic-recyc-03.svg | Polyvinyl chloride (PVC) | Plumbing pipes, children’s toys, non-food containers, and shower curtains | Sometimes recycled |
| Plastic-recyc-04.svg | Low-density polyethylene (LDPE) | Shopping bags, cling-film, sandwich bags, and squeezable bottles | Sometimes recycled |
| Plastic-recyc-05.svg | Polypropylene (PP) | Food containers, dishware, and medicine bottles | Not widely recycled |
| Plastic-recyc-06.svg | Polystyrene (PS) | Disposable hot beverage cups, plastic cutlery, packaging foam, children’s toys, and insulation board | Not widely recycled |
| Plastic-recyc-07.svg | Other (O), such as acrylic, nylon, polycarbonate, and polylactide  | Compact discs (polycarbonate), rope (nylon), paint (acrylic), and food packaging (polylactide) | Rarely recycled |

Plastics waste stream comprises contributions of six dense plastic waste fractions (“PET bottles”, “HDPE bottles”, “other plastic bottles”, “expanded polystyrene (EPS)”, “other plastic packaging”, and “other non-packaging plastic”) and three plastic film waste fractions (“carrier bags”, “other packaging film”, and “refuse sacks and other plastic film”). Since the recycling of dense plastics is driven by polymer type, it was necessary to determine the composition of the six dense plastic waste fractions by polymer type (see Table A20).

**Table A20**

Composition by polymer type of the six dense plastic waste fractions.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | PET | HDPE | PVC | LDPE | PP | PS | Other |
| PET bottlesa | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| HDPE bottlesa | 0% | 100% | 0% | 0% | 0% | 0% | 0% |
| Other bottlesb | 0% | 0% | 33% | 0% | 67% | 0% | 0% |
| EPSa  | 0% | 0% | 0% | 0% | 0% | 100% | 0% |
| Other plastic packagingc | 53% | 5% | 6% | 1% | 23% | 10% | 2% |
| Other non-packaging plasticd | 0% | 0% | 0% | 0% | 100% | 0% | 0% |

a“PET bottles”, “HDPE bottles”, and “EPS” were assumed to be composed exclusively of PET, HDPE, and PS, respectively.

bThe composition of “other bottles” was estimated based on annual arisings of rigid plastic bottles by polymer type, as reported by WRAP (2013), excluding PET and HDPE.

cOther plastic packaging composition by polymer type was established using data reported by WRAP (2013), which relates to the composition of plastic packaging, as follows: 1) the composition of rigid plastics packaging by format was established from the composition of consumer (household) plastics packaging by packaging format, excluding plastic film and plastic bottles; and 2) the composition of each rigid plastic packaging format by polymer type was calculated based on arisings of each polymer type per rigid plastic packaging format.

dDue to a lack of more specific information, the composition of “other non-packaging plastic” was assumed to be exclusively PP.

### Mixed plastics

#### Material composition

The material composition of mixed plastics used in this study is presented in Table A21

**Table A21**

Material composition of mixed plastics.

|  |  |
| --- | --- |
| Material type | Composition (%) |
| Oher plastic packaging | 23 |
| Other plastic non-packaging | 4 |
| PET bottles | 35 |
| HDPE bottles | 27 |
| Other plastic bottles | 10 |
| Expanded polystyrene (EPS) | 1 |

Source: adapted from WRAP (2009) and WRAP (2010a).

#### Recycling system description

Collected mixed plastics are taken to a plastics recycling facility for sorting and processing into secondary plastic pellets for use in a range of manufacturing applications. The two process for mixed plastics recycling was modelled based on two process stages: the first, a sorting and preparatory phase, which was modelled based on primary data from a mixed plastic sorting plant detailed by Shonfield (2008); and the second, a mechanical reprocessing (recycling) phase, modelled based on a UK-based plastics recycling facility operated by LINPAC Plastics Recycling Ltd (EA, 2010).

#### Mixed plastics sorting

During the sorting phase, contaminants (non-plastics, dense plastic mis-sorts [LDPE, PS, and other], and plastic film) are removed through a combination of STADLER plastic film removal and TITECH near infra-red (NIR) optical sorting technologies. Inventory data for the sorting or mixed plastics are presented in Table A22; data are representative of state-of-the-art technology available in the UK.

#### Mechanical reprocessing

During mechanical reprocessing, the sorted plastic fractions (PET, HDPE, PVC, and PP) are first shredded and granulated to produce flakes, which are then chemically washed to remove paper labels, adhesives, and other hard to separate contaminants. Further density-based separation procedures are then carried out to separate remaining contaminants from each polymer waste stream. The flakes are then dried using warm air flows and centrifuges and any fines (dust and paper) are removed through air classification. Finally, the cleaned and dried flakes are fed into a screw extruder, which heats and pressurises the flakes, and forced through a screen. Additives are added to the homogenous plastic output, which is then cooled and cut to produce uniform pellets ready for use in the production of new products (EA, 2010).

Inventory data (not presented in detail due to copyright restrictions) for the mechanical reprocessing were adapted from the process “plastics (HDPE) recycling, Linpac” supplied by the EA (2010) for the WRATE LCI database. Data for the reprocessing of HDPE has been used as a proxy for the reprocessing of PET, PP, and PVC. A 12% material loss rate was assumed during mechanical reprocessing (Shonfield, 2008), whilst a 10% material quality loss was also assumed (Merrild *et al.*, 2012).

**Table A22**

Inventory data for sorting of one tonne of waste mixed plastics.

|  | Unit | Quantity |
| --- | --- | --- |
| *Plastic film separation* |  |  |
| Inputs |  |  |
| Electricity | kWh | 1.2 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficients |  |  |
| Plastic film to residual  | t t-1 | 0.99 |
| Plastic film to NIR sorting | t t-1 | 0.01 |
| Non-plastics to NIR sorting | t t-1 | 1 |
| Dense plastic - PET to NIR sorting | t t-1 | 1 |
| Dense plastic - HDPE to NIR sorting | t t-1 | 1 |
| Dense plastic - PVC to NIR sorting | t t-1 | 1 |
| Dense plastic - LDPE to NIR sorting | t t-1 | 0.89 |
| Dense plastic - LDPE to residual | t t-1 | 0.11 |
| Dense plastic - PP to NIR sorting | t t-1 | 1 |
| Dense plastic - PS to NIR sorting | t t-1 | 0.89 |
| Dense plastic - PS to residual | t t-1 | 0.11 |
| Dense plastic - other to NIR sorting | t t-1 | 0.89 |
| Dense plastic - other to residual | t t-1 | 0.11 |
|  |  |  |
| *NIR optical sorting* |  |  |
| Inputs |  |  |
| Electricity | kWh | 61.8 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficients |  |  |
| Plastic film to residual | t t-1 | 1 |
| Non-plastics to residual | t t-1 | 1 |
| Dense plastic - PET to mechanical reprocessing (recycling) | t t-1 | 0.77 |
| Dense plastic - PET to residual | t t-1 | 0.23 |
| Dense plastic - HDPE to mechanical reprocessing (recycling) | t t-1 | 0.79 |
| Dense plastic - HDPE to residual | t t-1 | 0.21 |
| Dense plastic - PVC to mechanical reprocessing (recycling) | t t-1 | 0.61 |
| Dense plastic - PVC to residual | t t-1 | 0.39 |
| Dense plastic - LDPE to residual | t t-1 | 1 |
| Dense plastic - PP to mechanical reprocessing (recycling) | t t-1 | 0.88 |
| Dense plastic - PP to residual | t t-1 | 0.12 |
| Dense plastic - PS to residual | t t-1 | 1 |
| Dense plastic – other to residual | t t-1 | 1 |

Source: adapted from Shonfield (2008).

Secondary plastic pellets were assumed to substitute for production of primary plastic pellets. Avoided primary production data for pellets of different polymer types are detailed in Table A23. The processes include the transportation of raw materials and other input materials to the plastic processors and the production of primary plastic granulate.

**Table A23**

Inventory data for primary plastic granulate production.

|  |  |  |
| --- | --- | --- |
| Polymer type | Primary production process | LCI source |
| HDPE | “Polyethylene, HDPE, granulate, at plant” | Hischier (2007) |
| PET | “Polyethylene terephthalate, granulate, amorphous, at plant” | Hischier (2007) |
| PVC | “Polyvinylchloride, emulsion polymerised, at plant” (87%) and “polyvinylchloride, suspension polymerised, at plant” (13%) | Hischier (2007) |
| PP | “Polypropylene granulate (PP), production mix, at plant” | JRC (2009) |

### Mixed plastic bottles

#### Material composition

The material composition of mixed plastic bottles used in this study is presented in Table A24

**Table A24**

Material composition of mixed plastic bottles.

|  |  |
| --- | --- |
| Material type | Composition (%) |
| PET bottles | 35 |
| HDPE bottles | 27 |

Source: adapted from WRAP (2009) and WRAP (2010a).

#### Recycling system description

Waste mixed plastic bottles are sent to a plastics sorting facility to separate out the PET and HDPE bottles. The separated PET and HDPE bottles are then sent to mechanical reprocessing facility. The processes for sorting and reprocessing of waste mixed plastic bottles are detailed in Section 5.3.3 and Section 5.3.4, respectively. Details of market substitution are also presented in Section 5.3.4

### PET

#### Material composition

PET was assumed to be composed of 100% PET bottles.

#### Recycling system description

PET is sent directly to a mechanical reprocessing facility. At the facility, the waste PET is shredded and granulated to produce flakes, which are then chemically washed to remove paper labels, adhesives, and other hard to separate contaminants. The flakes are then dried using warm air flows and centrifuges and any fines (dust and paper) are removed through air classification. Finally, the cleaned and dried flakes are fed into a screw extruder, which heats and pressurises the flakes, and forced through a screen. Additives are added to the homogenous plastic output, which is then cooled and cut to produce uniform flakes ready for use in the production of new products (EA, 2010).

Inventory data (not presented in detail due to copyright restrictions) for PET reprocessing were adapted from the process “plastics (PET) recycling, Delleve” supplied by the EA (2010) for the WRATE LCI database. A 5% material loss was assumed (EA, 2010), whilst a 10% material quality loss was also assumed (Merrild *et al.*, 2012).

Secondary PET flakes were assumed to substitute for production of primary PET flakes. Primary production data were taken from the ecoinvent v2.2 database (“polyethylene terephthalate, granulate, amorphous, at plant”) (Hischier, 2007). The process includes the transportation of raw materials and other input materials to the reprocessor and the production of primary PET granulate.

### HDPE

#### Material composition

HDPE was assumed to be composed of 100% HDPE bottles.

#### Recycling system description

Waste HDPE is sent to a HDPE mechanical reprocessing facility, modelled based on a UK-situated HDPE plastics recycling facility operated by LINPAC Plastics Recycling Ltd (EA, 2010). Details of the process are outlined in Section 5.3.4. Secondary HDPE pellets were assumed to substitute for production of primary HDPE pellets. Primary production data were taken from the ecoinvent v2.2 database (“Polyethylene, HDPE, granulate, at plant”) (Hischier, 2007). The process includes the transportation of raw materials and other input materials to the reprocessor and the production of primary HDPE granulate.

### PVC

Waste PVC is sent to a plastics sorting facility to a mechanical reprocessing facility. The processes for reprocessing of waste PET was modelled based on a UK-situated HDPE plastics recycling facility operated by LINPAC Plastics Recycling Ltd (EA, 2010), used as a proxy for PVC reprocessing. Details of the process are outlined in Section 5.3.4. Secondary PVC pellets were assumed to substitute for production of primary PVC pellets. Primary production data were taken from the ecoinvent v2.2 database (87% “Polyvinylchloride, emulsion polymerised, at plant” and 13% “polyvinylchloride, suspension polymerised, at plant”) (Hischier, 2007). The process includes the transportation of raw materials and other input materials to the reprocessor and the production of primary PVC.

### LDPE

#### Material composition

LDPE was assumed to be composed of 100% plastic film.

#### Recycling system description

Plastic film is sent to a plastic film recycling facility where it is reprocessed into secondary LDPE pellets. The process for recycling of plastic film was modelled based on an agricultural film (LDPE and linear low-density polyethylene [LLDPE]) recycling facility located in Scotland and operated by British Polythene Industries (BPI) plc. At the facility, the feedstock is fed into a hopper containing two shredders to reduce particle size before being transferred to a conveyor belt and into a sink-float tank. The sunken heavy contaminants are removed for disposal, whilst the floating shredded film and lighter contaminants are forwarded through a pre-wash centrifuge to expel water and fine contaminants; this process is then repeated a second time. The remaining material is then transferred into a wet granulator, which further reduces the size of the feedstock, and is then passed through a series of augers to remove any remaining contaminants and to exude remaining pre-wash water. The feedstock is then washed before being fed into a screw press where it is dried. Once dried, the feedstock is conveyed into an extruder and melted before being passed through a filter to remove contaminants. The melted plastic flakes are then cooled by water injection and cut into 5 mm diameter pellets. The pellets are then packaged and ready for transportation.

Inventory data (not presented in detail due to copyright restrictions) for the mechanical reprocessing were adapted from the process “LLDPE and LDPE recycling, agricultural film, BPI Poly Recycled Products, Dumfries” supplied by the EA (2010) for the WRATE LCI database. A material loss of 47% was assumed (EA, 2010), whilst a 10% loss in material quality was also assumed (Merrild *et al.*, 2012).

Secondary LDPE pellets were assumed to substitute for primary LDPE granulate. Primary production data were sourced from the ecoinvent v2.2 database (*Polyethylene, LDPE, granulate, at plant*) (Hischier, 2007). The process includes all material and energy inputs, waste, and emissions to air from the production of LDPE granulate.

### PP

Waste PP is sent to a plastics sorting facility to a mechanical reprocessing facility. The processes for reprocessing of waste PP was modelled based on a UK-situated HDPE plastics recycling facility operated by LINPAC Plastics Recycling Ltd (EA, 2010), used as a proxy for PP reprocessing. Details of the process are outlined in Section 5.3.4. Secondary PP pellets were assumed to substitute for production of primary PP pellets. Primary production data were taken from the ELCD v2 database (“Polypropylene granulate (PP), production mix, at plant”) (JRC, 2009). The process includes the transportation of raw materials and other input materials to the reprocessor and the production of primary PVC.

## Wood

### Summary

An overview of key technical parameters used to model waste wood recycling is presented in Table A25.

**Table A25**

Summary of wood recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Wood | 0 | Wood | Recycled MDF | Virgin MDF fibre | 0 |
| Chipboard & MDF | 0 | Wood | Recycled MDF | Virgin MDF fibre | 0 |
| Composite wood materials | 20 | Wood | Recycled MDF | Virgin MDF fibre | 0 |

### Wood

Collected wood waste is sent to a wood recycling facility for preliminary grading and sorting. Wood waste is sorted into four grades: Grade A material is sold on to high value markets, such as animal bedding and panel board production, or to biomass (EfW) facilities; Grade B material is of a lower value but can be used in panel board production or as a feedstock in a biomass (EfW) facility; Grade C material can only be used at biomass (EfW) facilities and is increasingly being exported to European biomass (EfW) markets where demand for such products is high; and Grade D, which is hazardous wood waste and is only suitable for incineration (with or without EfW) or disposal in a hazardous waste landfill (Defra, 2012). Municipal wood waste is generally of a low quality (Grades B and C) as it includes numerous different types of wood and wood-based products (WRAP, 2011). Hence, waste wood was here assumed to be Grade B material. It was therefore assumed that such material would be used in the production of panel board – the largest end market for recovered wood in the UK (WRAP, 2011).

Two principle sources of data for wood recycling into panel board (MDF) production were identified: Merrild and Christensen (2009) detail the use of recovered wood in the production of particle board based on data from Northern Europe; and Mitchell and Stevens (2009), who describe the use of recovered wood and MDF in the production of recycled MDF in the UK. The process for waste wood recycling was modelled based on those data from Mitchell and Stevens (2009) as they were determined as being more representative of the UK situation.

#### Fibre preparation

Wood fibres are recovered from waste MDF through a microrelease process that utilises microwave heating and are used in the production of MDF boards that contain a portion of recycled fibres. The microrelease processes comprises four stages: 1) the waste MDF board feedstock is shredded to release dust and remove metallic contaminants, which are disposed to landfill, and separate the wood fibres; 2) separated MDF board fragments are immersed in water for saturation; 3) the feedstock is heated in a microwave field, during which the board is caused to swell and the fibres are separated; and 4) finally, the separated fibres are reclaimed through mechanically separated prior to drying. Inventory data for the separation and preparation of waste MDF fibres using the microrelease process are presented in Table A26.

**Table A26**

Inventory data for sorting of one tonne of waste wood/MDF using the microrelease process.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |  |  |
| Water | m3 | 1.5 |
| Diesel | kg | 1.3 |
| Heat, natural gas | GJ | 4.4 |
| Electricity | kWh | 331 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficients |  |  |
| Wood to accepts | t t-1 | 1 |
| Contaminants to rejects | t t-1 | 1 |
|  |  |  |
| Outputs |  |  |
| Wastewater, to treatment | m3 | 1.5 |

Source: adapted from Mitchell and Stevens (2009).

#### Board production

The prepared waste MDF fibres are used in the production of MDF boards that contain a portion of recycled fibres. During the process, the fibres are first introduced to a mat former for gravitational settlement (mat production). The mat is then transferred to a precompressor where it is pressurised in the absence of heat to press the fibres into a board-like structure. The board-like structure is then pressured under heat to activate the binding resin. Inventory data pertaining to the production of recycled MDF board is displayed in Table A27.

Recycled MDF board containing waste MDF fibres were assumed to substitute for virgin MDF board producing using virgin wood. No material quality loss was assumed. Avoided primary production data for virgin MF production are detailed in Table A28. The processes include the transportation of raw materials to the facility, the preparation of virgin wood fibres (including debarking, chipping, washing, defibrillation, and drying) and the use of virgin wood fibres in MDF board production.

**Table A27**

Inventory data for use of one tonne of sorted waste wood/MDF in the production of recycled MDF.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |  |  |
| Heat, natural gas | MJ | 960 |
| Electricity | kWh | 107 |
|  |  |  |
| Outputs |  |  |
| MDF | kg | 1000 |
| Wood ash, to landfill | kg | 0.0018 |
| Sludge, to landfill | kg | 0.024 |
| Wastewater, to treatment | kg | 318 |

Source: adapted from Mitchell and Stevens (2009).

**Table A28**

Inventory data for use of production of one tonne of virgin MDF.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |  |  |
| Softwooda | m3 | 0.83 |
| Hardwoodb | m3 | 0.22 |
| Softwood chipsa | m3 | 0.13 |
| Urea | kg | 110 |
| Transport, lorry | tkm | 76 |
| Electricity | kWh | 433 |
| Heat, natural gas | GJ | 4.8 |
| Propane | kg | 7.5 |
|  |  |  |
| Outputs |  |  |
| Virgin MDF | kg | 1000 |

Source: adapted from Mitchell and Stevens (2009).

aBased on a softwood density of 0.7 t/m3.

bBased on a hardwood density of 1 t/m3.

### Chipboard & MDF

Chipboard & MDF recycling was modelled using the wood recycling system, as described in Section 6.2, where all process inventory data used to model wood recycling were applied consistently for chipboard & MDF.

### Composite wood materials

#### Material composition

The variety of materials that may be classified as “composite wood products” possess a wide array of physical and chemical properties. Broadly, composite wood products are constructed using wood fibres, flakes, chips, shavings, as well as veneers and papers and are often combined with adhesives, water repellents and preservatives. Furthermore, depending on the nature of their prior use, composite wood materials may be disposed of with other components, such as nails, screws, paint, and plastic coatings. Examples of common composite wood products include;

* fibreboard (constructed of wood fibres),
* particle board (constructed of wood chips and shavings and a wood resin binder), and
* plywood (constructed of layered wood veneer bound with glue) (Campbell, 2007).

The material composition of composite wood materials used in this study is presented in Table A20.

**Table A29**

Material composition of mixed plastics.

|  |  |
| --- | --- |
| Material type | Composition (%) |
| Ferrous metals | 5 |
| Wood | 80 |
| Other combustibles | 15 |

Source: adapted from EA (2010).

#### Recycling system description

Composite wood materials recycling was modelled using the wood recycling system process, as described in Section 6.2, where all process inventory data used to model wood recycling were applied consistently for composite wood materials.

## WEEE

### Summary

An overview of key technical parameters used to model WEEE recycling is presented in Table A30.

**Table A30**

Summary of WEEE recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Large domestic appliances | 48.0 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Plastic | PP granulate | PP granulate | 10 |
| Small domestic appliances | 48.8 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Plastic | PP | PP | 10 |
| Batteries | Zinc | Zinc | 0 |
| Manganese | Manganese | 0 |
| Mercury | Mercury | 0 |
| Ferromanganese  | Ferromanganese | 0 |
| Crude steel | Steel | 0 |
| Cathode ray tubes | 67.6 | Lead | Lead | Lead | 0 |
| Copper | Copper | Copper | 0 |
| Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Cables | Copper | Copper | 0 |
| Fluorescent tubes & other light bulbs | 4.5 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Glass | Secondary container glass | Primary container glass | 0 |
| Fridges & freezers | 40.7 | Steel | Crude steel | Steel | 0 |
| Aluminium | Aluminium | Aluminium | 0 |
| Plastic | PP granulate | PP granulate | 10 |

### Large domestic appliances

#### Material composition

The average composition of large domestic appliance is based on the composition of large white goods disposed of in the UK, as detailed in Table A31; data are representative of the year 2006.

**Table A31**

Average composition of large white goods disposed of in the UK.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Ferrous metals | 54.2 |
| Non-ferrous metals | 7.4 |
| Other plastic non-packaging | 12.4 |
| Printed wiring board (PWB) | 0.1 |
| Other | 25.9 |

Source: Defra (2007).

#### Recycling system description

Collected WEEE is sent to either; i) a producer compliance scheme (PCS) approved authorised treatment facility (AATF) for disassembly (dismantling), during which the desirable material components are separated and, subsequently, sent for processing (refinement and recycling).

#### Dismantlement (disassembly) and processing

The WEEE dismantlement (disassembly) process at an AATF was modelled based on a theoretical modern mechanical treatment plant sited in Switzerland, as described by Hischier *et al.* (2007). Input WEEE is first manually treated in order that the device is thoroughly depolluted. Following this are a mechanical shredding stage and a disassembly stage, during which the device is separated into its different constituent material fractions (Hischier *et al.*, 2007). Inventory data for WEEE disassembly (dismantlement) at a mechanical treatment plant are detailed in Table A32.

Post-shredding, the target materials (ferrous metals, non-ferrous metals, and plastics) are separated out and sent on to for reprocessing. Details of the reprocessing of each of these materials (including market substitution) are presented in Section 4.2, Section 4.3, and Section 5.3, respectively. Material loss rates during the disassembly process were inferred from the transfer coefficients detailed by Hischier *et al.* (2007): ferrous metals, 5%; non-ferrous metals, 17%; and plastics, 82%. No material quality loss was assumed as this was attributed downstream at the respective material reprocessing facilities. Printed wiring boards (PWB) are sent for specialist treatment (see Section 7.2.4). Residual waste is disposed of to landfill.

**Table A32**

Inventory data for depolluting, dismantling and sorting of one tonne of WEEE.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 660 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficients |  |  |
| PWB to specialist treatment | t t-1 | 1 |
| Batteries to specialist treatment | t t-1 | 1 |
| Ferrous metals to ferrous metals reprocessing | t t-1 | 0.95 |
| Ferrous metals to non-ferrous metals reprocessing (contaminant) | t t-1 | 0.01 |
| Ferrous metals to plastics reprocessing (contaminant) | t t-1 | 0.005b |
| Ferrous metals to glass reprocessing (contaminant) | t t-1 | 0.005b |
| Ferrous metals to residual | t t-1 | 0.03b |
| Non- ferrous metals to non- ferrous metals reprocessing | t t-1 | 0.83 |
| Non- ferrous metals to ferrous metals reprocessing (contaminant) | t t-1 | 0.005 |
| Non- ferrous metals to plastics reprocessing (contaminant) | t t-1 | 0.005b |
| Non- ferrous metals to glass reprocessing (contaminant) | t t-1 | 0.005b |
| Non- ferrous metals to residual | t t-1 | 0.155b |
| Plastics to plastics reprocessing | t t-1 | 0.18a |
| Plastics to ferrous metals reprocessing (contaminant) | t t-1 | 0.012 |
| Plastics to non- ferrous metals reprocessing (contaminant) | t t-1 | 0.005 |
| Plastics to glass reprocessing (contaminant) | t t-1 | 0.005b |
| Plastics to residual | t t-1 | 0.798b |
| Glass to glass reprocessing | t t-1 | 0.95c |
| Glass to ferrous metals reprocessing (contaminant) | t t-1 | 0.0056 |
| Glass to non- ferrous metals reprocessing (contaminant) | t t-1 | 0.0056 |
| Glass to plastics reprocessing (contaminant) | t t-1 | 0.0056b |
| Glass to residual | t t-1 | 0.0332b |
| Other to ferrous metals reprocessing (contaminant) | t t-1 | 0.0069 |
| Other to non- ferrous metals reprocessing (contaminant) | t t-1 | 0.0067 |
| Other to plastics reprocessing (contaminant) | t t-1 | 0.01b |
| Other to glass reprocessing (contaminant) | t t-1 | 0.01b |
| Other to residual | t t-1 | 0.9664b |

Source: adapted from Hischier *et al.* (2007).

aBased on Crowe *et al.* (2003).

bBased on estimation.

cBased on Hischier *et al.* (2007) and Lu *et al.* (2015).

####  Printed wiring board (PWB) treatment

The process for the treatment of PWBs separated out at the WEEE disassembly plant was modelled based on a theoretical thermal treatment (metallurgical processing) facility, as detailed by Hischier *et al.* (2007). Inventory data for the chemical (metallurgical) processing of waste PWBs is detailed in Table A33; data are representative of average global conditions in the year 2005.

**Table A33**

Inventory data for chemical (metallurgical) processing of one tonne of waste PWBs.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 40 |

Source: Hischier *et al.* (2007).

### Small domestic appliances

#### Material composition

The average composition of small domestic appliances disposed of in the UK was estimated based on the average of reported literature data (Crowe *et al.*, 2003; Environment & Heritage Service, 2005; Freegard and Claes, 2009; Wäger *et al.*, 2009); see Table A34.

**Table A34**

Average composition of small domestic appliances disposed of in the UK.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Ferrous metals | 41 |
| Non-ferrous metals | 16 |
| Other plastic non-packaging | 35 |
| Batteries | 1 |
| Other | 7 |

Source: adapted from Freegard and Claes (2009),Crowe *et al.* (2003), Environment & Heritage Service (2005), and Wäger *et al.* (2009).

#### Recycling system description

Collected small domestic appliances are sent to an AATF for disassembly and sorting (for details, see Section 7.2.3). Target materials (ferrous metals, non-ferrous metals, and plastics) are sent on for reprocessing (for details, see Section 4.2, Section 4.3, and Section 5.3, respectively), batteries are sent on for further treatment and recycling (see Section 8.3), and rejects are disposed of to landfill.

### Cathode ray rubes (CRTs)

#### Material composition

Prior to the rapid advancement of liquid-crystal display (LCD), light-emitting diode (LED), and plasma display panel (PDP) video display technologies since the start of the twenty-first century, CRTs were widely used as a video display component in the manufacture of televisions and computers. CRTs are generally disposed of along with the product within which they were contained (e.g. a television or a computer monitor).

To represent the composition of an average end-of-life CRT-containing product, composition data of a 17-inch CRT screen was used (see Table A35); data are based on a European study conducted in the year 2005 (Hischier *et al.*, 2007). The CRT component constitutes approximately 55% (w/w) of the overall composition of a television or monitor and consists of approximately 85% (w/w) leaded glass (Andreola *et al.*, 2005; Andreola *et al.*, 2007; Wang and Xu, 2014).

**Table A35**

Material composition of a 17-inch CRT Screen.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Steel | 18.81 |
| Aluminium | 1.98 |
| Copper | 0.33 |
| Other metals | 0.86 |
| Plastics | 16.39 |
| Cable | 2.31 |
| PWB | 4.69 |
| CRT glass | 53.36 |
| Other | 1.27 |

Source: adapted from Hischier *et al.* (2007).

#### Recycling system description

CRT glass, which contains high quantities of lead, is recognised as being a difficult material to recycle (Xu *et al.*, 2013; Wang and Xu, 2014). Historically, there was a demand for glass-to-glass (closed-loop) recycling as recovered CRT glass could be used in the production of new video display products. However, with the decline in the use of CRTs, the demand for leaded glass in the video display manufacturing industry has all but ceased (Wang and Xu, 2014). Rather, it is more common for CRT glass to be used in primary or secondary lead smelters as a substitute for primary inputs or fluxing agents (Nnorom *et al.*, 2011).

The recycling process for CRT screens is based on the treatment of a 17-inch CRT Screen, as detailed by Hischier *et al.* (2007). Post-collection, CRT screens are sent to an AATF for manual disassembly and depollution followed by mechanical treatment and sorting. Recyclable materials are then sent on to reprocessing facilities and residuals are sent for disposal.

#### Mechanical treatment

The process of CRT screen disassembly and depollution was modelled based on a theoretical treatment facility (AATF), as detailed by Hischier *et al.* (2007), based on qualitative information from several German recycling companies. The process starts with a manual depollution step, during which the fractions that are unsuitable for mechanical shredding are removed from the input devices and sent for further treatment, reprocessing, or disposal. The remaining waste is commingled and fed into a mechanical shredder. The shredded output is placed onto a conveyer that passes under a drum magnet and an eddy current separator to recover ferrous metals and aluminium, respectively. The waste is then shredded a second time before a second series of metals recovery takes place, with copper recovered through eddy current separation. Finally, the remaining waste is passed through a sifter, contained, and sent on for disposal. Inventory data pertaining to the manual depollution, mechanical shredding, and sorting of waste CRT screens are detailed in Table A36 (Hischier *et al.*, 2007).

#### CRT glass recycling

CRT glass that is separated from CRT screens during manual depollution is sent to a lead smelter for incineration. The process for pyrometallurgical processing of CRT glass in a lead smelter was modelled based on data reported by Xu *et al.* (2013). During the smelting process, metallic lead and copper are separated and recovered, whilst the CRT glasses behaves as a fluxing agent during incineration (Nnorom *et al.*, 2011; Xu *et al.*, 2013). Inventory data for pyrometallurgical processing of CRT glass are detailed in Table A37; data are representative of average global conditions for the year 2012. A 20% material loss was assumed for the lead fraction of the CRT glass (Xu *et al.*, 2013). No material quality loss was assumed. Recovered secondary lead was assumed to be used in manufacturing where it would substitute for primary lead. The primary production data were sourced from the ecoinvent v2.2 database (“lead, primary, at plant”) and are representative of average global conditions in the year 2000 (Classen *et al.*, 2009).

**Table A36**

Inventory data for mechanical treatment (depollution and shredding) of one tonne of waste 17-inch CRT screens at a mechanical treatment plant.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| *Manual depollution* |
| Process parameters |
| Transfer coefficients |
| Plastics to disposal | t t-1 | 0.469 |
| Plastics to shredder | t t-1 | 0.531 |
| Cables to cable treatment | t t-1 | 0.142 |
| Cables to shredder | t t-1 | 0.858 |
| Steel to steel reprocessing | t t-1 | 0.463 |
| Steel to shredder | t t-1 | 0.537 |
| CRT glass to CRT glass treatment | t t-1 | 1 |
| Aluminium to shredder | t t-1 | 1 |
| Copper to shredder | t t-1 | 1 |
| Other metals to shredder | t t-1 | 1 |
| PWB to shredder | t t-1 | 1 |
| Other to shredder | t t-1 | 1 |
|  |  |  |
| *Mechanical shredding* |
| Inputs |
| Electricity | kWh | 66 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficients |  |  |
| Plastics to steel reprocessing (contaminant) | t t-1 | 0.012 |
| Plastics to aluminium reprocessing (contaminant) | t t-1 | 0.005 |
| Plastics to copper reprocessing (contaminant) | t t-1 | 0.1 |
| Plastics to disposal | t t-1 | 0.883 |
| Other metals to steel reprocessing (contaminant) | t t-1 | 0.011 |
| Other metals to aluminium reprocessing (contaminant) | t t-1 | 0.01 |
| Other metals to copper reprocessing (contaminant) | t t-1 | 0.811 |
| Other metals to disposal | t t-1 | 0.168 |
| Aluminium to steel reprocessing (contaminant) | t t-1 | 0.005 |
| Aluminium to aluminium reprocessing | t t-1 | 0.826 |
| Aluminium to copper reprocessing (contaminant) | t t-1 | 0.049 |
| Aluminium to disposal | t t-1 | 0.12 |
| Copper to steel reprocessing (contaminant) | t t-1 | 0.009 |
| Copper to aluminium reprocessing (contaminant) | t t-1 | 0.05 |
| Copper to copper reprocessing | t t-1 | 0.782 |
| Copper to disposal | t t-1 | 0.159 |
| Cables to disposal | t t-1 | 1 |
| PWB to disposal | t t-1 | 1 |
| Other to disposal | t t-1 | 1 |

Source: adapted from Hischier *et al.* (2007).

**Table A37**

Inventory data for pyrometallurgical processing of one tonne of CRT glass.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Silica sand | kg | 500 |
| Electricity | kWh | 420 |
|  |  |  |
| Outputs |  |  |
| Secondary lead | kg | 176a |
| Slag, to inert landfill | kg | 800 |

Source: adapted from Xu *et al.* (2013).

#### Cables treatment

Waste cable that is separated from CRT screens during manual depollution is sent to a specialist cable treatment facility. The process for cables treatment was modelled based on data from a European cable recycling company, as detailed by Hischier *et al.* (2007). The process comprises the shredding of waste cable to reduce their size, followed by a granulation and the separation step whereby copper is separated from the residual plastic fraction. The recovered copper is then sent to secondary copper smelter for use in copper production. Inventory data for the treatment of one tonne of waste cable is presented in Table A38; data are representative of average European conditions for the year 2005 (Hischier *et al.*, 2007). Material loss and material quality loss of copper during processing was assumed to be negligible.

**Table A38**

Inventory data for treatment of one tonne of waste cable.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 180 |
|  |  |  |
| Outputs |  |  |
| Copper, to copper reprocessor | kg | 660 |
| Plastics, to disposal | kg | 340 |

Source: Hischier *et al.* (2007).

#### Copper recycling

Copper recovered during the treatment of waste cable and CRT screens was assumed to be sent to a secondary copper smelter for use in secondary copper production. The process for secondary copper production was modelled based on data from a large German secondary copper smelter, as detailed by Hischier *et al.* (2007). The process entails the refinement of copper scrap and the production of copper cathodes. Inventory data for the refinement of one tonne of copper scrap are presented in Table A39; data are representative of average European conditions in 1998.

Secondary copper was assumed to be used in the production of copper cathodes where it would substitute for primary copper. The primary production data were sourced from the ecoinvent v2.2 database (“copper, primary, at refinery”) and are representative of average European conditions in the year 1998 (Classen *et al.*, 2009).

**Table A39**

Inventory data for refinement of one tonne of copper scrap in a secondary scrap smelter.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Blister-copper | kg | 87 |
| Silica sand | kg | 47.7 |
| Limestone | kg | 56.4 |
| Electricity | kWh | 840 |
| Heat, hard coal | MJ | 4980 |
| Heat, heavy fuel oil | MJ | 1970 |
|  |  |  |
| Outputs |  |  |
| Secondary copper | kg | 763 |
| Wastewater, to treatment | m3 | 0.8 |

Source: adapted from Hischier *et al.* (2007).

### Fluorescent tubes & other light bulbs

#### Material composition

The average composition of fluorescent tubes disposed of in the UK is detailed in Table A40; data are based on a European study conducted in the year 2002 (Crowe *et al.*, 2003), which have been used to represent average UK conditions.

**Table A40**

Average composition of end-of-life fluorescent tubes.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Ferrous metals | 0.6 |
| Non-ferrous metals | 1.4 |
| Glass | 93.9 |
| Other | 4.1 |

Source: Crowe *et al.* (2003).

#### Recycling system description

Two types of treatment techniques are used in the fluorescent lamp recycling industry: dismantling, during which the lamps are manually dismantled to separate the various constituent parts; and shredding, during which the lamps are mechanically shredded prior to the removal of the various material fractions (Hischier *et al.*, 2007). It was here assumed that fluorescent tubes and light bulbs were dismantled manually, as detailed below.

#### Dismantlement (disassembly) and processing

The process of fluorescent tube recycling was modelled based on a theoretical dismantlement facility, as detailed by Hischier *et al.* (2007), based on qualitative information from several German recycling companies. The process comprises an initial cutting stage to remove the metal-containing caps from the fluorescent tubes, followed by the removal of the coating through manual dismantlement. The separated glass is crushed to obtain glass cullet, which is sent for reprocessing. The exhaust air, which is emitted during the disassembly stage, is scrubbed to separate the mercury and phosphor (Hischier *et al.*, 2007; Apisitpuvakul *et al.*, 2008). Inventory data for fluorescent tube disassembly at a mechanical treatment plant are detailed in Table A41; data are representative of average conditions in Switzerland (used as a Proxy for the global situation) for the year 2005.

**Table A41**

Inventory data for disassembly of one tonne of fluorescent tubes and light bulbs at a mechanical treatment plant.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 30 |
|  |  |  |
| Outputs |  |  |
| Dust, to disposal | kg | 10 |
| Mercury, to hazardous landfill | kg | 5 |
| Glass cullet, to reprocessing | kg | 890 |
| Rare-earth activated phosphors, to hazardous landfill | kg | 15 |
| Secondary metalsa, to reprocessing | kg | 80 |

Source: Hischier *et al.* (2007).

aAssumed to comprise 30% ferrous and 70% non-ferrous metals based on Crowe *et al.* (2003).

The product outputs from the fluorescent tube disassembly process (ferrous metals, non-ferrous metals, and glass) are sent on to for reprocessing. Details of the reprocessing of each of these materials (including market substitution) are presented in Section 4.2, Section 4.3, and Section 2.5.2 respectively. Limited information was available pertaining to material loss during the disassembly process but were assumed to be negligible (Hischier *et al.*, 2007). No material quality loss was assumed as this was attributed downstream at the respective material reprocessing facilities. Whilst it is possible to recycle the separated mercury and phosphors through distillation and purification (see, for example, Binnemans *et al.*, 2013; Tunsu *et al.*, 2014), such practice is uncommon and was therefore not included in this study. Instead, it was assumed that mercury and phosphors were disposed of in a hazardous waste landfill.

### Fridges & freezers

#### Material composition

The average composition of refrigerators and freezers disposed of in the UK is detailed in Table A42; data are based on a European study conducted in the year 2002 (Crowe *et al.*, 2003), which have been used to represent average UK conditions.

**Table A42**

Average composition of end-of-life refrigerators and freezers.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Ferrous metals | 64.4 |
| Non-ferrous metals | 6.0 |
| Plastics | 13.0 |
| Glass | 1.4 |
| Other | 15.1 |

Source: Crowe *et al.* (2003).

#### Recycling system description

Collected fridges and freezers are sent to an AATF for disassembly and sorting (for details, see Section 7.2.3). Target materials (ferrous metals, non-ferrous metals, and plastics) are sent on for reprocessing (for details, see Section 4.2, Section 4.3, and Section 5.3, respectively) and rejects are disposed of to landfill.

## Batteries

### Summary

An overview of key technical parameters used to model waste batteries recycling is presented in Table A43.

**Table A43**

Summary of batteries recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Material component | Secondary product | Substituted primary product | Material quality loss (%) |
| Automotive batteries | 35.0 | Batteries | Lead | Lead | 0 |
| Post-consumer, non-automotive batteries | 42.0 | Batteries | Manganese | Manganese | 0 |
| Zinc | Zinc | 0 |
| Crude steel | Steel | 0 |
| Mercury | Mercury | 0 |
| Ferromanganese | Ferromanganese | 0 |

###  Automotive batteries

#### Material composition

The assumed composition of collected automotive batteries is detailed in Table A42; data are representative of an average lead acid battery disposed of in the UK in 2006.

**Table A42**

Lead acid battery composition.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Lead | 65 |
| Other metals | 4 |
| Sulphuric acid | 16 |
| Plastics | 10 |
| Other | 5 |

Source: Fisher *et al.* (2006).

#### Recycling system description

Post-collection, automotive batteries are sent to a batteries sorting facility in the UK. Once sorted, the automotive batteries are transported to a lead-acid battery reprocessing facility.

#### Spent batteries sorting

The process for sorting waste batteries was modelled based on data from G&P Batteries, a batteries sorting plant based in the UK (Fisher *et al.*, 2006). At the facility, batteries are first unloaded at the reception area via an on-site forklift and are passed through to a warehouse for sorting, which is predominantly manual. Batteries are sorted according to their chemistries and non-target materials are removed for disposal at either a hazardous waste incinerator or a non-hazardous landfill. Post-sorting, the batteries are stockpiled in the warehouse inside polyethylene containers until they are sufficiently full for economic transfer to reprocessing facilities. At this stage, the bins are loaded onto vehicles via an on-site forklift and are transported to the relevant recycling facility based on the batteries' chemistry (Fisher et al. (2006). Inventory data for the G&P Batteries sorting process are detailed in Table A43. Target material loss during sorting was assumed to be negligible.

**Table A43**

Inventory data for sorting of one tonne of mixed waste batteries.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |  |  |
| HDPE | kg | 1.25 |
| Electricity | kWh | 2.4 |
| Diesel | l | 0.17 |
| Coke | kg | 20.0 |
| Water | kg | 0.47 |
|  |  |  |
| Process parameters |  |  |
| Transfer coefficients |  |  |
| Batteries to batteries recycling | t t-1 | 1 |
| Contaminants to residual | t t-1 | 1 |
|  |  |  |
| Outputs |  |  |
| Wastewater, to treatment | kg | 0.47 |
| Emissions to air |  |  |
| Carbon dioxide, fossil | kg | 0.46 |

Source: adapted from Fisher *et al.* (2006).

#### Spent batteries processing

The process for recycling of wet-cell lead acid automotive batteries was modelled based on data from Campine, a lead recycling plant based in Belgium, and is representative of the year 2004 (Fisher *et al.*, 2006). At the facility, the waste battery feedstock is first mechanically shredded, with any leaked sulphuric acid captured and pumped into storage tanks where it remains until it is transported off-site for re-use in industry. The shredded batteries are mixed with coke fuel, limestone, and re-used process slag and transferred in batches into a furnace, where the mixture is melted at a temperature of 1,200 to 1,300°C. The main outputs from the furnace are lead (86-87% pure), slags (approximately 78% of which are re-used internally as an input into the lead furnace), and waste gases (quenched, filtered, and cooled with cold air to prevent dioxin formation). The lead is transferred to a refinery where antimony and calcium impurities are removed through oxidation. The final lead oxide product is then removed mechanically and cast into ingots (depending on the intended application, alloys may be added at this step). Inventory data for the Campine lead acid recycling process are detailed in Table A44. Target material (lead) loss during sorting was assumed to be negligible and no material quality loss is assumed.

Recovered secondary lead was assumed to substitute for primary lead. The primary production data were sourced from the ecoinvent v2.2 database (“lead primary, at plant”) and are representative of global conditions in the year 2005 (Classen *et al.*, 2009). The process encompasses the production of primary lead via sintering, direct smelting, and final refinement and includes the disposal of slag.

**Table A44**

Inventory data for reprocessing of one tonne of spent lead acid batteries.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Limestone | kg | 5.8 |
| Iron (Fe) scrap | kg | 4.0 |
| Sodium hydroxide | kg | 350 |
| Sodium nitrate  | kg | 0.4 |
| Sulphur | kg | 0.9 |
| Iron chloride | kg | 0.9 |
| Slag (re-used from process) | kg | 150 |
| Electricity | kWh | 35.2 |
| Natural gas | kg | 16.2 |
| Coal coke | kg | 20.0 |
| Process water | kg | 770 |
|  |  |  |
| Outputs |  |  |
| Secondary Fe | kg | 650 |
| Flue dust (re-used internally) | kg | 13.6 |
| Slag (re-used internally) | kg | 150 |
| Slag, to inert landfill | kg | 44 |
| sulphuric acid (re-used internally) | kg | 71 |
| Emissions to air |
| Carbon dioxide, fossil | kg | 500 |

Source: Fisher *et al.* (2006).

### Post-consumer, non-automotive batteries

#### Material composition

A 2008 study by WRAP (2008a) found that alkaline/zinc carbon batteries comprised over 92% of post-consumer spent dry-cell batteries collected in the UK in 2008. Given their market dominance, the recycling of post-consumer batteries recycling was modelled based on the recycling of spent alkaline batteries. The average composition of spent alkaline batteries collected in the UK in 2008 is detailed in Table A45. It should be noted that large variations in composition are evident between different battery producers (Fisher *et al.*, 2006).

**Table A45**

Alkaline manganese battery composition.

|  |  |
| --- | --- |
| Component | Percentage |
| Ferrous metals | 24.8 |
| Manganese (Mn) | 22.3 |
| Nickel (Ni) | 0.5 |
| Zinc (Zn) | 14.9 |
| Other metals | 1.3 |
| Alkali | 5.4 |
| Carbon | 3.7 |
| Paper | 1.0 |
| Plastics | 2.2 |
| Water | 10.1 |
| Other non-metals | 14.0 |

Source: Fisher *et al.* (2006).

#### Recycling system description

Post-collection, spent post-consumer batteries are sent to a batteries sorting facility in the UK. Batteries are then sorted according to their individual chemistries before being transported for processing.

#### Spent batteries sorting

The process for sorting post-consumer spent batteries was based on data from G&P Batteries (see Table A43). Target material loss during sorting was assumed to be negligible (Fisher *et al.*, 2006).

#### Spent batteries processing

Given that each different type of battery has its own composition, a variety of techniques must be applied in the processing of waste batteries (see Fisher *et al.*, 2006; Baeyens *et al.*, 2010). To minimise data requirements, it was assumed that 50% of waste post-consumer, non-automotive batteries are treated by hydrometallurgical processing and 50% by pyrometallurgical processing (Fisher *et al.*, 2006; Hischier *et al.*, 2007), with the purpose being to recover metals for re-use and recycling (ERC, 2012).

##### Hydrometallurgical processing

Hydrometallurgical processing of used batteries was modelled based on the battery recycling process, RECUPYLTM, developed by Recupyl, France, as detailed by Fisher *et al.* (2006). The process begins with the shredding and sorting of the input waste batteries according to size. The feedstock then undergoes a mechanical treatment step comprising the sifting and magnetic separation of the ferrous metals, paper, and plastics from the shredded batteries to leave a 'black mass'. The black mass is then treated with acid, leaving a zinc/mercury solution, a separation of mercury, and a separation of other (non-ferrous) metals. The zinc/mercury solution is then purified via electrolysis to leave zinc and mercury oxides that are sent for use in the non-ferrous metals production industry. Inventory data for the RECUPYLTM recycling process are detailed in Table A46; data are representative of French conditions in the year 2004. Material loss during the process was assumed to be negligible (Fisher *et al.*, 2006). No material quality loss was assumed.

Recovered zinc was assumed to be sold to the non-ferrous metals industry for galvanisation where it was assumed to substitute for primary zinc. The primary production data were sourced from the ecoinvent v2.2 database (“zinc, primary, at regional storage”) and are representative of average European conditions in the year 2003 (Classen *et al.*, 2009). The process includes the transportation and use of raw material and energy inputs in the production of high grade primary zinc through pyrometallurgical and hydrometallurgical processes, the disposal of slag, and the treatment of wastewater.

The elemental manganese from the manganese dioxide output was assumed to be used in the non-ferrous metals industry where it was assumed to substitute for primary manganese. The primary production data were sourced from the ecoinvent v2.2 database (“manganese, at regional storage”) and are representative of average European conditions in the year 2003 (Classen *et al.*, 2009). The process includes the transportation and use of raw material and energy inputs in the production of manganese through electrolysis of ore and electrothermic processing of ferromanganese.

Recovered ferrous metals were assumed to be used in the production of crude steel. Details of the use of ferrous metal scrap in the production of crude steel, including market substitution, are outlined in Section 4.2.

**Table A46**

Inventory data for hydrometallurgical processing (RECUPYLTM process) of one tonne of spent alkaline batteries.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Sulphuric acid (92%) | l | 168 |
| Hyponitrite (N2O2) (30%) | l | 126 |
| Antifoam | l | 0.86 |
| Electricity | kWh | 959 |
| Water | l | 567 |
|  |  |  |
| Outputs |  |  |
| Secondary zinc | kg | 205 |
| Manganese dioxide (MnO2), to non-ferrous metals industry | kg | 317 |
| *of which pure Mn* | *kg* | *228* |
| Ferrous metals, to steel production | kg | 180 |
| Residuals, to disposal | kg | 120 |
| Residue of leaching (chemical treatment), to disposal | kg | 97 |
| Mixed heavy metals, to disposal | kg | 10 |
| Wastewater, to treatment | kg | 99 |

Source: Fisher *et al.* (2006).

##### Pyrometallurgical processing

Modelling of pyrometallurgical recycling of alkaline and saline batteries was based on the process at Batrec, Switzerland, a used battery recycler, as detailed by Fisher *et al.* (2006). The feedstock is first manually sorted before being fed into a shaft furnace, where they are pyrolysised at temperatures of up to 700°C. During pyrolysis, the water and mercury are vaporised and, along with carbonised organic compounds, pass into an afterburner. The exhaust gases are then led into an exhaust gas purification plant where they are washed with circulating water to remove solid materials and allow the mercury to condense into a metallic form. The metallic components arising through the pyrolysis process are passed into an induction furnace, where they are reduced through smelting at a temperature of 1,500°C. Iron and manganese separate during the smelting process and combine to form ferro-manganese, whilst the zinc vaporises and is recovered in a zinc condenser. Inventory data for the Batrec pyrometallurgical recycling process are detailed in Table A47; data are representative of Swiss conditions in the year 2004. Material loss during the process was assumed to be negligible (Fisher *et al.*, 2006). No material quality loss was assumed.

It was assumed that the product output, ferromanganese, would be used as a deoxidiser in the cast iron industry. Secondary ferromanganese was assumed to substitute for primary ferromanganese at a ratio of 0.74:1 (w/w), based on the respective manganese contents of the two sources: secondary ferromanganese was reported by Fisher *et al.* (2006) as having an Mn content of 55%, whilst primary ferromanganese has an Mn content of 74.5% according to Classen *et al.* (2009). The primary production data were sourced from the ecoinvent v2.2 database (“ferromanganese, high-coal, 74.5% Mn, at regional storage”) and are representative of average European conditions in the year 2003 (Classen *et al.*, 2009).

Recovered zinc was assumed to be sold to the non-ferrous metals industry for galvanisation where it was assumed to substitute for primary zinc. The primary production data were sourced from the ecoinvent v2.2 database (“zinc, primary, at regional storage”) and are representative of average European conditions in the year 2003 (Classen *et al.*, 2009). The process includes the transportation and use of raw material and energy inputs in the production of high grade primary zinc through pyrometallurgical and hydrometallurgical processes, the disposal of slag, and the treatment of wastewater.

It was assumed that recovered metallic mercury would be sold to the metallurgic industry where it would substitute for primary mercury. The primary production data were sourced from the ecoinvent v2.2 database (“mercury, liquid, at plant”) and are representative of average global conditions in the year 2003.

**Table A47**

Inventory data for pyrometallurgical processing of one tonne of spent alkaline batteries.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Fuel oil | kg | 58 |
| Propane | kg | 6 |
| Electricity | kWh | 1690 |
| Water | l | 1400 |
|  |  |  |
| Outputs |  |  |
| Ferromanganese (55% Fe, 40% Mn, 5% Cu, & Ni) | kg | 290 |
| Secondary zinc | kg | 200 |
| Secondary mercury | kg | 0.3 |
| Wastewater, to treatment | l | 1400 |
| Slag, to disposal | kg | 146 |
| Emissions to air |
| Nitrous oxide | kg | 0.82 |

Source: Fisher *et al.* (2006).

## Tyres

### Summary

An overview of key technical parameters used to model waste tyres recycling is presented in Table A48.

**Table A48**

Summary of tyres recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Material component | Secondary product | Substituted primary product | Material quality loss (%) |
| Car tyres | 22.1 | Steel | Crude steel | Steel | 0 |
| Crumb rubber | Rubber granulate <3 mm | Bitumen | 0 |
| Rubber crumb <20 mm | Synthetic rubber | 0 |
| Van tyres | 13.0 | Steel | Crude steel | Steel | 0 |
| Crumb rubber | Rubber granulate <3 mm | Bitumen | 0 |
| Rubber crumb <20 mm | Synthetic rubber | 0 |
| Large vehicle tyres | 13.0 | Steel | Crude steel | Steel | 0 |
| Crumb rubber | Rubber granulate <3 mm | Bitumen | 0 |
| Rubber crumb <20 mm | Synthetic rubber | 0 |
| Mixed tyres | 21.0 | Steel | Crude steel | Steel | 0 |
| Crumb rubber | Rubber granulate <3 mm | Bitumen | 0 |
| Rubber crumb <20 mm | Synthetic rubber | 0 |

### Car tyres

#### Material composition

The average composition of a UK end-of-life passenger car tyre is detailed in Table A49; data are representative of the year 2005.

**Table A49**

End-of-life passenger car tyre material composition.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Crumb rubber | 70 |
| Steel | 17 |
| Fibre & scrap | 13 |

Source: Evans and Evans (2006).

#### Recycling system description

Collected waste car tyres are sent to a waste rubber recycling facility. There is a dearth of specific data pertaining to the tyre recycling process. As such, the tyre recycling process was modelled based on process descriptions from Baeyens *et al.* (2010), Eldan Recycling (2014b), and Silvestravičiūtė and Karaliūnaitė (2006) coupled with secondary literature data used as a proxy; hence, the degree of associated uncertainty is large. At the waste rubber recycling facility, waste tyres are first fed into a chopper for preliminary shredding into less than 100 mm chips. The chips are then fed into a granulator, where their size is further reduced (to less than 10 mm) and the steel and fibre is liberated from the rubber crumb. After leaving the granulator, steel is recovered through magnetic separation and the fibre fraction is removed through a combination of shaking screens and wind shifters. The remaining rubber crumb may them pass through a number of further grinding steps to reduce the particle size (typically to within a range of 0.6 – 4.0 mm) and reduce levels of contamination with steel and fibre. The extent to which rubber crumb is further processed is dependent on customer demand, with the quality of the output (particle size and level of contamination) varying from product to product (Reschner, 2002; Pehlken and Müller, 2009).

Typical product grades in demand in the UK include <3 mm rubber granulate (applied across a range of industries, including landscaping, horticulture, transport, and construction); <20 mm rubber crumb (commonly used in landscaping and artificial sports surfacing); tyre-derived fuel (TDF) for combustion in cement kilns; and recovered steel, which is further cleaned to reduced contamination prior to reprocessing in steel production.

Inventory data for the tyre recycling process are detailed in Table A50. As mentioned above, the type of rubber product produced is customer driven and is highly variable. Qualitative evidence suggests that rubber granulate, which is applied predominantly in the transport industry in road construction, is the most in-demand product from waste tyres (Pehlken and Müller, 2009; Baeyens *et al.*, 2010); as such, it was assumed that 75% of rubber was used in rubber granulate production, whilst the remaining 25% was used in rubber crumb production. Due to a lack of specific data, material loss rates were estimated to be 10% for both steel and rubber. No material quality loss was assumed.

Rubber granulate, <3 mm was assumed to be used in the transport industry as an additive to asphalt in road surfacing. The rubber granulate was assumed to substitute for primary asphalt (bitumen) at a ratio of 1:1 (mass basis). The primary production data were sourced from the ecoinvent v2.2 database (“bitumen, at refinery”) and are representative of average European conditions in the year 2000.

Rubber crumb, < 20 mm was assumed to be used in the leisure and recreation industry in sports surfacing. It was assumed to substitute for synthetic rubber at a ratio of 1:1 (mass basis). The primary production data were sourced from the ecoinvent v2.2 database (“synthetic rubber, at plant”) and are representative of average European conditions in the year 2003.

Recovered steel was assumed to be used in the production of crude steel. Details of the use of steel in the production of crude steel, including market substitution, are outlined in Section 4.2.

**Table A50**

Inventory data for processing of one tonne of waste tyres.

|  |  |  |  |
| --- | --- | --- | --- |
|   | Unit | Quantity | Reference |
| Inputs |
| Electricity | kWh | 200 | Eldan Recycling (2014a) |
|  |  |  |  |
| Outputs |  |  |  |
| Steel, to steel production | kg | 153a | - |
| Rubber granulate (<3 mm) | kg | 473b | - |
| Rubber crumb (<20 mm)  | kg | 158b | - |
| Steel, to disposal | kg | 17 | - |
| Rubber, to disposal | kg | 70 | - |
| Fibre, to disposal | kg | 130 | - |

aContains minor (2-3%) contamination of rubber (Baeyens *et al.*, 2010).

bContains minor (1-4%) contamination of fibre and steel (Eldan Recycling, 2014a).

### Van tyres

Recycling of van was modelled using “large vehicle tyres” recycling as a proxy (see Section 9.4 for details).

### Large vehicle tyres

#### Material composition

The average composition of a UK end-of-life large vehicle tyres vehicle tyre is detailed in Table A51; data are representative of the year 2005.

**Table A51**

End-of-life large vehicle tyres material composition.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Crumb rubbera | 78 |
| Steel | 15 |
| Fibre & scrap | 7 |

Source: Evans and Evans (2006).

aContains minor contamination of metals and fibres.

#### Recycling system description

Collected waste large vehicle tyres are sent to a waste rubber recycling facility. Their processing was assumed to be consistent with that of passenger car tyres (see Section 9.2.2). Due to the different material composition between large vehicle tyres and car tyres, the outputs of the tyre recycling process are different. Inventory data for large vehicle tyre recycling process are detailed in Table A52. Details of market substitution from secondary materials production are detailed in Section 9.2.2.

**Table A52**

Inventory data for processing of one tonne of large vehicle tyres.

|  |  |  |  |
| --- | --- | --- | --- |
|   | Unit | Quantity | Reference |
| Inputs |
| Electricity | kWh | 200 | Eldan Recycling (2014a) |
|  |  |  |  |
| Outputs |  |  |  |
| Steel, to steel production | kg | 135a | - |
| Rubber granulate (<3 mm) | kg | 526b | - |
| Rubber crumb (<20 mm)  | kg | 176b | - |
| Steel, to disposal | kg | 15 | - |
| Rubber, to disposal | kg | 78 | - |
| Fibre, to disposal | kg | 70 | - |

aContains minor (2-3%) contamination of rubber (Baeyens *et al.*, 2010).

bContains minor (1-4%) contamination of fibre and steel (Eldan Recycling, 2014a).

### Mixed tyres

The composition (by vehicle tyre type) of mixed tyres was determined based on the UK tyre market composition in 2010 and is detailed in Table A53.

**Table A53**

End-of-life large vehicle tyres material composition.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Car tyres | 88 |
| Van tyres | 8 |
| Large vehicle tyres | 3 |

Source: adapted from TIF (2011).

Details of the car tyres, van tyres, and large vehicle tyres recycling systems are provided in Section 9.2, Section 9.3, and Section 9.4, respectively.

## Furniture

### Summary

An overview of key technical parameters used to model waste furniture recycling is presented in Table A54.

**Table A54**

Summary of furniture recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Furniture | 20 | Wood | Recycled MDF | Virgin MDF fibre | 0 |

### Furniture

Recycling of furniture was modelled using “composite wood materials” recycling as a proxy (see Section 6.4 for details).

## Rubble

### Summary

An overview of key technical parameters used to model waste furniture recycling is presented in Table A54.

**Table A54**

Summary of furniture recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Rubble | 7.1 | Rubble (stones) | Aggregate  | Gravel | 0 |
| Ferrous metals | Crude steel | Steel | 0 |

### Rubble

#### Material composition

The average composition of UK waste rubble is detailed in Table A55; data are representative of the year 2004.

**Table A55**

Average composition of UK waste rubble.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Rubble (stones) | 93.0 |
| Soil | 4.5 |
| Wood | 1.0 |
| Ferrous metals | 1.0 |
| Plastics | 0.5 |

Source: adapted from EA (2010).

#### Recycling system description

Post-collection, rubble is sent to a mobile mechanical treatment plant. The rubble is first sorted to remove contaminants, which are disposed of to landfill, before being crushed to the required size for use. The ferrous metals are separated out and sent for reprocessing and use in the production of secondary steel. Inventory data for the waste rubble recycling process are detailed in Table A56; data re representative of average UK conditions in the year 2004. No material loss or material quality loss was assumed (EA, 2010).

Recycled rubble was assumed to be used as aggregate (type 1 sub base) in the construction industry. The secondary aggregate was assumed to substitute for primary aggregate (gravel). The primary production data were sourced from the ecoinvent v2.2 database (“gravel, unspecified, at mine”) and are representative of average Swiss conditions in the year 1997 (Kellenberger *et al.*, 2007).

**Table A56**

LCI data for reprocessing of one tonne of rubble into secondary aggregate.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs  |  |  |
| Water | kg  | 0.15 |
| Diesel | kg | 0.58 |
|  |  |  |
| Outputs |  |  |
| Type 1 sub base | kg | 930 |
| Ferrous metals, to steel production | kg | 10 |
| Residuals, to disposal | kg | 60 |
| Emissions to air |  |  |
| Carbon dioxide, fossil | kg | 1.82 |

Source: EA (2010).

## Soil

### Summary

An overview of key technical parameters used to model soil recycling is presented in Table A57.

**Table A57**

Summary of furniture recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Soil | 0 | Soil | - | - | - |

### Soil

#### Recycling system description

Soil was assumed to be used as an alternative daily cover (ADC) on landfill sites. 0.35 kg diesel fuel was assumed to be used during application (Boldrin *et al.*, 2009). The degradation and fate of carbon and nitrogen in the soil post-applied to land was modelled based on research conducted in West Denmark (Bruun *et al.*, 2006; Hansen, 2006) and Europe (Smith *et al.*, 2001) used as a proxy. The proportion of biogenic carbon bound to soil after 100 years was assumed to be 12% (Smith *et al.*, 2001; Bruun *et al.*, 2006). No market substitution was assumed.

## Plasterboard

### Summary

An overview of key technical parameters used to model plasterboard recycling is presented in Table A58.

**Table A58**

Summary of plasterboard recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Plasterboard | 3.0 | Gypsum | Gypsum | Mineral gypsum | 0 |
| Paper | Testliner | Kraftliner | 10 |
| Wellenstoff | Semi-chemical fluting | 10 |

### Plasterboard

#### Material composition

Plasterboard is composed of an inner layer of gypsum sandwiched between two outer layers of lining paper. Different board products may include various additives, designed to enhance the robustness of the board, which results in a wide variation in board compositions and properties. The material composition of an average UK plasterboard panel is detailed in Table A59; data are representative of an average plasterboard panel in the UK in the year 2007.

 **Table A59**

Average UK plasterboard material composition.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Gypsum | 93.0 |
| Lining paper | 6.6 |
| Other | 0.4 |

Source: adapted from WRAP (2008b).

#### Recycling system description

Post-collection, post-consumer waste plasterboard is sent to a plasterboard recycling facility. Upon receipt of the waste, contaminants (comprising mostly metallic nails and screws) and the lining paper are liberated from the gypsum through a series of mechanical processes, including grinding, shredding, and sieving. The contaminants are then disposed of to landfill, whilst the recovered lining paper is sent for recycling (see Section 3.5), composting, or disposal in a landfill (based on WRAP (2008b), it was here assumed that lining paper is transferred evenly between these three outcomes. The remaining gypsum, which typically contains less than 3% contamination, is then sold and transported to plasterboard manufacturers for pre-processing (drying) and calcination before being incorporated in the production of new plasterboard products.

Inventory data for post-consumer waste plasterboard recycling are detailed in Table A60, whilst inventory data for the pre-processing of gypsum at a plasterboard manufacturing facility is detailed in Table A61. Material loss rate for gypsum was assumed to be negligible, whilst a 33% material loss was assumed for paper (WRAP, 2008b). No material quality loss was assumed for gypsum (WRAP, no date-d) or paper, where material quality loss was attributed downstream at the paper reprocessing facility.

Recovered gypsum was assumed to be recycled in a closed-loop system and used in the production of new plasterboard products. Recovered and processed gypsum was assumed to substitute for imported mineral gypsum. The substituted product comprises several datasets: 1) Mining. Mineral gypsum was assumed to be sourced from a European quarry (WRAP, 2008b), with data pertaining to the mining and crushing of mineral gypsum sourced from the ecoinvent v2.2 database (“gypsum, mineral, at mine”); data are representative of average conditions in Switzerland in the year 2003 (Kellenberger *et al.*, 2007); 2) Transportation. Mined gypsum sourced from a European mine was assumed to be transported 16 km by lorry and 2,730 km by ship from a European mine to the plasterboard manufacturer (WRAP, 2008b); and 3) Pre-processing (drying). Upon arrival at a plasterboard manufacturer, mineral gypsum is dried to reduce its moisture content prior to calcination. Inventory data pertaining to the pre-processing (drying) of mineral gypsum are derived from WRAP (2008b) and are detailed in Table A62; data are representative of UK conditions in the year 2007.

**Table A60**

Inventory data for processing of one tonne of post-consumer waste plasterboard at a plasterboard recycling facility.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 9.9 |
| Diesel | l | 0.9 |
|  |  |  |
| Outputs |  |  |
| Gypsum, to pre-processing | kg | 930 |
| Paper, to disposal | kg | 22 |
| Paper, to composting | kg | 22 |
| Paper, to recycled cardboard base paper production | kg | 22 |
| Residuals, to disposal | kg | 4 |

Source: adapted from WRAP (2008b).

**Table A61**

Inventory data for pre-processing (drying) of one tonne of post-consumer waste gypsum at a plasterboard manufacturing facility.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 10 |
| Natural gas | m3 | 3.3 |
|  |  |  |
| Outputs |  |  |
| Gypsum, to calcination | kg | 1000 |

Source: WRAP (2008b).

**Table A62**

Inventory data for pre-processing (drying) of one tonne of mineral gypsum at a plasterboard manufacturing facility.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 4.8 |
| Natural gas | m3 | 0.8 |
|  |  |  |
| Outputs |  |  |
| Mineral gypsum, to calcination | kg | 1000 |

Source: WRAP (2008b).

## Oil

### Summary

An overview of key technical parameters used to model waste oil recycling is presented in Table A63.

**Table A63**

Summary of waste oil recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Material component | Secondary product | Substituted primary product | Material quality loss (%) |
| Vegetable oil | 4.1 | Vegetable oil | Biodiesel | Fossil diesel | 0 |
| Mineral oil | 4.1 | Mineral oil | Biodiesel | Fossil diesel | 0 |

### Vegetable oil

#### Recycling system description

Collected vegetable oil was assumed to be recycled in the production of biodiesel. There are several possible means of obtaining biodiesel from lipidic feedstocks (see Morais *et al.*, 2010). The most commonly used method is the transesterification of triglycerides in the presence of a homogenous alkali-catalyst, which produces methyl ester molecules comparable in size to diesel fuel. Several sources of LCI data pertaining to the use of waste vegetable oil in the production of biodiesel were identified (Jungbluth *et al.*, 2007; Morais *et al.*, 2010; Talens Peiró *et al.*, 2010; Wang, 2013). Of these, data from Morais *et al.* (2010) were adopted for this study as they was assessed as being of the highest quality (in terms of representativeness and appropriateness) of the available data sources. For details of the process, refer to Morais *et al.* (2010). Inventory data for the biodiesel production process using waste vegetable oil process are detailed in Table A64; data are representative of average European conditions in the year 2010. A 4.1% material loss was assumed (Morais *et al.*, 2010), whilst no material quality loss rate was assumed.

Biodiesel derived from waste vegetable oil was assumed to be used in the transport industry as B20 fuel – a mixture of 20% biodiesel and 80% petroleum-based diesel by volume. The biodiesel was assumed to substitute for fossil fuel-derived diesel oil. Substitution of fuels may be accounted on a mass, volume or energy content basis, and it is recognised that the choice of substitution method can have a significant effect on the results (Kim and Dale, 2002; Gnansounou *et al.*, 2009). It was here assumed that biodiesel would substitute for diesel oil at a 1:1 ratio on an energy content basis (net calorific value), as per the recommendation of Gnansounou *et al.* (2009). The energy content of biodiesel was assumed to be 44 MJ kg-1 (DEFRA *et al.*, 2014). The primary production data were sourced from the UK GHG conversion factors database and are representative of average UK conditions in the year 2014 (DEFRA *et al.*, 2014). Based on this, the energy content of fossil fuel-derived diesel oil was assumed to be 42.94 MJ kg-1, meaning that in this study biodiesel was assumed to substitute for fossil diesel at a ratio 1:0.976 (mass basis).

**Table A64**

Inventory data for use of one tonne of waste vegetable oil in biodiesel production using an alkali-catalysed transesterification process with free fatty acids pre-treatment.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Water (process) | kg | 41.4 |
| Water (cooling) | kg | 2,677 |
| Methanol | kg | 108.0 |
| Sodium hydroxide | kg | 8.4 |
| Sulphuric acid | kg | 0.1 |
| Phosphoric acid | kg | 6.8 |
| Calcium oxide | kg | 0.1 |
| Electricity | kWh | 0.9 |
| Glycerol | kg | 0.1 |
| Medium pressure stream (250°C) (from natural gas) | kg | 796.6 |
| Low pressure stream (100°C) (from natural gas) | kg | 1491 |
|  |  |  |
| Outputs |  |  |
| Biodiesel | kg | 959.5 |
| Salts, to disposal | kg | 13.6 |
| Hazardous liquid waste, to wastewater treatment | kg | 32.3 |

Source: Morais *et al.* (2010).

### Mineral oil

Pratt *et al.* (2013) provide carbon factors for the recycling of mineral waste derived from household waste (2 kg CO2e t-1) and non-household (C&I and C&D) waste (1 kg CO2e t-1), with these factors based on a German LCA study carried out in 2005 by IFEU (Fehrenbach, 2005). However, the IFEU study compares the environmental impacts of five different used oil re-refinement techniques and it is unknown which of these was used by Pratt *et al.* (2013) in the development of their carbon factor. Furthermore, due to the high processing costs involved in re-refinement (Fitzsimons, 2010), it is unlikely that this practice represents the predominant management option for used mineral oil in the UK.

An alternative source of data is a 2013 Californian LCA study of used oil managed undertaken by CalRecycle (Geyer *et al.*, 2013). and other co-products present life-cycle inventory models for the reprocessing of used oil into either marine distillate oil (distillation), re-refined base oil (re-refinement), or recycled fuel oil (RFO). However, the primary data used in their modelling is not documented due to restrictions imposed by non-disclosure agreements. Furthermore, the assumptions made in the study are based on the average situation in the USA and are not representation or appropriate for application in a UK study.

Due to the lack of both general information and LCA studies pertaining to the management of used mineral oil in the UK, the vegetable oil recycling system (Section 14.2) was been used as a proxy.

## Composite

### Summary

An overview of key technical parameters used to model waste composite materials recycling is presented in Table A65.

**Table A65**

Summary of waste composite materials recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Material component | Secondary product | Substituted primary product | Material quality loss (%) |
| Composite food & beverage cartons | 30.7 | Paper | Testliner | Kraftliner | 10 |
| Wellenstoff | Semi-chemical fluting | 10 |
| Plastic | HDPE granulate | HDPE granulate | 10 |
| Aluminium | Aluminium | Aluminium | 0 |
| Mattresses | 33.4 | Textiles | Mattress filling fibre | Flocking material | 20 |
| Natural fibre wiping cloths | Paper wiping cloths | 20 |
| Artificial fibre wiping cloths | Artificial wiping cloths | 20 |
| Steel | Crude steel | Steel | 0 |

### Composite food & beverage cartons

#### Material composition

The material composition of an average composite food & beverage carton (Tetra Brik Aspec package) is detailed in Table A66.

**Table A66**

Average material composition of a Tetra Brik Aspec (TBA) package.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Paperboard | 74 |
| Plastic (HDPE) | 21 |
| Aluminium | 5 |

Source: adapted from Barkman *et al.* (1999).

#### Recycling system description

Collected composite food and beverage cartons are sent to a composite packaging recycling facility for dismantlement. The recovered materials (paper, plastic, and aluminium) are then sent on for recycling at material-specific recycling facilities.

#### Composite packaging dismantlement

The process for composite packaging dismantlement was modelled based on a theoretical European waste paper sorting facility, as described by Hischier (2007), used as a proxy for composite packaging dismantlement. At the facility, the composite packaging feedstock is first soaked in water to liberate the paperboard from the plastic and aluminium layers. The paperboard is then sent to a paper mill for reprocessing, the plastic (assumed to be HDPE) is sent to a HDPE mechanical reprocessing (recycling) facility, and the aluminium is sent for re-melting. Inventory data for composite carton recycling process are detailed in Table A67; data are representative of average European conditions in the year 2007. Material loss rates of 20%, 2%, and 38% were reported by Xie *et al.* (2012) for paperboard, aluminium, and HDPE, respectively; these values were adopted in this study. No material quality loss was assumed as this was attributed downstream at the respective constituent material reprocessing facilities.

**Table A67**

Inventory data for recycling (dismantling and shredding) of one tonne of composite food & beverage cartons.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Unit | Quantity | Reference |
| Inputs |  |
| Electricity | kWh | 9.1 | Adapted from Hischier (2007) |
| Diesel | kg | 0.62 | Adapted from Hischier (2007) |
| Heat, light fuel oil | MJ | 0.36 | Adapted from Hischier (2007) |
| Rolled steel | kg | 1.2 | Adapted from Hischier (2007) |
| Hydraulic oil | kg | 0.012 | Adapted from Hischier (2007) |
|  |  |  |  |
| Outputs |  |  |  |
| Paper, to recycled cardboard base paper production | kg | 592 | Adapted from Xie *et al.* (2012) |
| HDPE, to HDPE recycling | kg | 31 | Adapted from Xie *et al.* (2012) |
| Aluminium, to aluminium recycling | kg | 206 | Adapted from Xie *et al.* (2012) |
| Paper, to disposal | kg | 148 | Adapted from Xie *et al.* (2012) |
| HDPE, to disposal | kg | 19 | Adapted from Xie *et al.* (2012) |
| Aluminium, to disposal | kg | 4 | Adapted from Xie *et al.* (2012) |

#### Material recycling

Recovered paperboard was assumed to be sent to a paper mill for reprocessing into secondary cardboard products (see Section 3.3.1). Recovered aluminium was assumed to be sent to an aluminium reprocessor for use in the production of secondary aluminium ingots (see Section 4.3.3). Recovered HDPE was assumed to be sent to a HDPE mechanical reprocessing facility for use in the production of secondary HDPE pellets (see Section 5.6.2).

### Mattresses

#### Material composition

Mattresses are composite materials that typically consist of three layers: the core, which provides the support and is commonly composed of steel springs, polyether foam, and/or latex foam; the shell, which provides the padding around the core and comprises a composite textile structure (materials typically used include (non-exclusively) polyether foam, latex foam, cotton fibre, and wool) that is glued and/or sewed on to the core and fixed with stapes; and the tick, which comprises the outer comfortable, cushioning cover layer of the mattress and is commonly composed of (non-exclusively) cotton, polyester, silk, wool, or polypropylene. The composition for post-consumer waste mattresses used in this study is detailed in Table A68.

**Table A68**

Average composition of post-consumer waste mattresses in the UK.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Steel | 50 |
| Textilesa | 35 |
| Otherb | 15 |

Source: adapted from Bartlett *et al.* (2013).

a Comprise unwoven cotton fibre (29%), polyester (14%), mixed cover textiles (29%), and flock (28%) (Bartlett *et al.*, 2013).

b Includes (non-exclusively) polyurethane foam (~ 33%), wool, wood, plastic film, and rigid plastics (~ 67% combined) (Bartlett *et al.*, 2013).

#### Recycling system description

The process for recycling of collected post-consumer waste mattresses was modelled based on Chapman and Bartlett (2011), WRAP (no date-c), and (WRAP, no date-b) and comprises four operational stages: checking and unloading; deconstruction; materials separation and processing; and distribution of materials to end markets. Post-delivery and unloading at the recycling site, the mattresses are checked for suitability and contamination. According to WRAP (no date-b), approximately 2-3% of mattresses are rejected at this stage and landfilled due to excessive contamination. Following checking, mattresses are stored prior to deconstruction, which begins with a manual sorting phase to separate the mattresses into different types (steel, foam, etc.). The sorted mattresses are then manually deconstructed to separate the core, shell, and tick materials, which are stored in separate areas; further processing and sorting of the textile components is often required. Once sorted, the different materials are then collected by materials recyclers for further reprocessing downstream.

Due to a lack of specific data, inventory data for the sorting of recovered textiles (detailed in Section 17.2.3). were used as a proxy for the checking and deconstruction of waste mattresses. Based on WRAP (no date-b), it was assumed that 2% of mattresses are rejected during the checking stage. Of the mattresses that undergo deconstruction, WRAP (no date-c) report a recycling rate of 60-80%. Based on this, the following separation for recycling efficiencies were assumed; steel, 95%, textiles, 80%, other materials, 0%.

Recovered steel was assumed to be sent to a steel smelter for use in the production of crude steel (see Section 3.3), whilst recovered textiles were assumed to be sent to a textiles sorting facility for further sorting prior to recycling (see Section 17.2).

## Paint

### Summary

An overview of key technical parameters used to model paint recycling is presented in Table A69.

**Table A69**

Summary of paint recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Paint | 82.6 | Steel | Crude steel | Steel | 0 |

### Paint

#### Material composition

Post-consumer paint packaging waste consists of used small metal containers (steel) that may be empty or may contain a small quantity of paint sludge. Paint sludge contains a combination of organic material, inert material, and water, with the precise composition highly variable and dependent upon the paint product type. The average composition of post-consumer paint packaging waste disposed of in the Netherlands in the year 2003 (detailed in Table A70) was used as a proxy for the UK situation.

**Table A70**

Average composition of post-consumer paint packaging waste in the Netherlands in the year 2003.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Metal (steel) | 20 |
| Water | 6 |
| Organic material (hydrocarbons) | 48 |
| Inert material (ash) | 26 |

Source: Saft (2007).

#### Recycling system description

Upon collection, post-consumer waste paint is sent to a liquid waste physico-chemical treatment plant. The process for treating and recycling of post-consumer waste paint was modelled based on a description of the activities carried out at a liquid waste physico-chemical treatment plant located at Gwent, UK and operated by Tradebe. At the plant, waste paint is shredded to reduce particle size and to separate the metal containers from the paint sludge. The metal containers are then cleaned (to remove stubborn paint sludge), crushed, and compacted before being sent for recycling. The paint sludge is treated through a combination of physical (froth flotation and centrifugation) and chemical (acid neutralisation and metals precipitation) treatment processes before being blended and filter-pressed, which produces a sterile effluent that is discharged for treatment at a POTW and a filter cake that is disposed to landfill.

Due to a lack of specific data, a number of secondary data sources were used as proxies for the physico-chemical treatment process. Energy and material inputs for the sorting and preparing of aluminium scrap metal process were used as a proxy for the mechanical shredding of paint containers (See Section 4.3.2). Steel recovered during mechanical shredding was assumed to be sent to a steel smelters for use in the production of crude steel. Details of the steel recycling process are detailed in Section 4.3. The various mechanical and chemical treatment processes were represented using data adapted from a Class 5 wastewater treatment plant sourced from the ecoinvent v2.2 database (Doka, 2009). Inventory data for the physico-chemical treatment of waste paint sludge are presented in Table A71.

**Table A71**

Inventory data for the physico-chemical treatment of one tonne of post-consumer waste paint sludge.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs |
| Electricity | kWh | 210 |
| Heat, natural gas | MJ | 3.4 |
| Organic chemicals | kg | 0.00025 |
| Inorganic chemicals | kg | 9.7 |
| Quicklime | kg | 0.0006 |
|  |  |  |
| Outputs |  |  |
| Wastewater, to treatment | kg | 60a |
| Inert material, to inert landfill | kg | 740b |
| Emissions to air |  |  |
| Carbon dioxide, biogenic | kg | 170 |
| Nitrous oxide | kg | 0.11 |
| Methane, biogenic | kg | 0.50 |

Source: adapted from Doka (2009).

aBased on the water content of the feedstock.

bBased on the inert and organic material content of the feedstock.

## Textiles

### Summary

An overview of key technical parameters used to model waste textiles recycling is presented in Table A72.

**Table A72**

Summary of waste textiles recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Material component | Secondary product | Substituted primary product | Material quality loss (%) |
| Textiles & footwear | 9.3 | Textiles | Mattress filling fibre | Flocking material | 20 |
| Natural fibre wiping cloths | Paper wiping cloths | 20 |
| Artificial fibre wiping cloths | Artificial wiping cloths | 20 |
| Textiles only | 9.3 | Textiles | Mattress filling fibre | Flocking material | 20 |
| Natural fibre wiping cloths | Paper wiping cloths | 20 |
| Artificial fibre wiping cloths | Artificial wiping cloths | 20 |
| Footwear only | 9.3 | Textiles | Mattress filling fibre | Flocking material | 20 |
| Natural fibre wiping cloths | Paper wiping cloths | 20 |
| Artificial fibre wiping cloths | Artificial wiping cloths | 20 |

### Textiles and footwear

#### Material composition

The average composition of UK waste textiles and footwear is detailed in Table A73; data are assumed to be representative of the year 2007.

**Table A73**

Average composition of UK waste textiles and footwear.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Textiles | 87.5 |
| Shoes | 9.8 |
| Plastic film | 2.0 |
| Paper | 0.4 |
| Non-ferrous metals | 0.2 |
| Dense plastic | 0.1 |

Source: adapted from EA (2010).

#### Recycling system description

Collected textiles are sent to a textiles recovery (reclamation and reprocessing) facility in the UK where they are sorted for re-use or recycling. Textiles sorted for re-use are further sorted according to their quality. The highest quality articles are sent for re-use within the UK, whilst articles of a lower quality are exported for re-use abroad. Textiles sorted for recycling are, similarly, sorted further by quality, with higher quality material sent for recycling in secondary wiper production and lower quality materials sent for recycling as mattress filling fibre. In this study, it was assumed that textiles were only sorted for recycling.

#### Recovery (reclamation and processing)

The textiles and footwear sorting process was modelled based on a UK-based textiles recovery plant operated by Jmp Wilcox & Co. Ltd. (EA, 2010). At the facility, an initial hand sorting procedure is performed to remove contaminants and unsuitable textiles, which are disposed of to landfill, from the post-consumer textiles feedstock. The feedstock is then roughly sorted into broad categories based on the type of textile/footwear (e.g., clothing, carpets, and wipers). Each of the textile categories is then finely sorted in different grades based on their required condition, quality, and fibre composition according to the specifications of the various end markets (McGill, 2009; Morley *et al.*, 2009; Bartlett *et al.*, 2013). Inventory data are not presented for copyright reasons.

Of the material sorted to be sent for recycling, it was assumed that 70% was used in the production of wiping cloths and 30% used in the production of mattress filling fibre (adapted from McGill, 2009). Recycling of recovered textiles and footwear into carpet underlay or various automotive applications was not considered as part of this study.

#### Wiping cloth production

The reprocessing of waste textiles into industrial wipers and rags was modelled based on a UK-based textiles recycling facility operated by Jmp Wilcox & Co Ltd (EA, 2010). Upon receipt of the sorted textiles, contaminants, such as buttons and zips, are removed manually with metal detectors used to verify the removal of metallic components. The textiles are then manually cut to a specified size, ready for resale as wipers to industry (Bartlett *et al.*, 2013). Inventory data are not presented for copyright reasons.

Textiles for the production of secondary wipers and rags are assumed to be composed of 40% cotton fibres and 60% artificial fibres. Cotton and artificial fibres were assumed to substitute for paper wipers and primary polypropylene production. A material quality loss of 20% was assumed (McGill, 2009). The primary production data for paper wipers were sourced from the ecoinvent v2.2 database (“kraft paper, bleached, at plant”) and are representative of average European conditions in the year 1993 (Hischier, 2007). Primary production data for polypropylene were also sourced from the ecoinvent v2.2 database (“polypropylene, granulate, at plant”) and are representative of average European conditions in the year 1999 (Hischier, 2007).

#### Mattress filling fibre production

The reprocessing of waste textiles into mattress filling fibre (flocking) was modelled based on a UK-based textiles recycling facility operated by Edward Clay and Sons Ltd. (EA, 2010). At the facility, the input material is first mechanically shredded and blended. Zips and buttons are removed mechanically through suction and cyclone separation. The shredded fibres are then entwined via needle-punching before being mechanically cut to the required size (Bartlett *et al.*, 2013). Inventory data are not presented due to copyright. A material loss rate of 7% was assumed (EA, 2010).

Mattress flocking material derived from post-consumer textiles was assumed to be used in the manufacturing of new mattresses. The secondary mattress flocking was assumed to substitute for primary flocking material. A 20% material quality loss was assumed (McGill, 2009). The primary production data were sourced from the ecoinvent v2.2 database (“polyurethane, flexible foam, at plant”) and are representative of average European conditions in the year 1997 (Hischier, 2007). The bulk densities of recovered textile-derived mattress flocking and primary flocking material (polyurethane flexible foam) are 1.42 kg m-2 and 1.19 kg m-2, respectively. As such, it was assumed that primary flocking material would be substituted at a ratio of 1:67 (w/w) (McGill, 2009).

### Textiles only

Recycling of textiles only was modelled using “textiles and footwear recycling as a proxy (see Section 17.2 for details).

### Footwear only

Recycling of footwear only was modelled using “textiles and footwear recycling as a proxy (see Section 17.2 for details).

### Carpets

#### Material composition

Carpets are composite materials typically comprised of four layers: face fibre (may be composed of nylon, mixed synthetics, wool, or polypropylene; see Table A74), primary backing (the face fibre bonding layer; typically composed of modified bitumen, PVC, or polypropylene), secondary backing (the rear bonding layer; typically composed of polypropylene), and adhesive (commonly composed of a styrene-butadiene rubber (SBR) compounded with inorganic material, such as calcium carbonate [CaCO3]) (Jain *et al.*, 2012; Mundy *et al.*, 2014). The approximate component composition of polypropylene and SBR constructed carpets, which represent over 50% of total carpet waste in the UK, is shown in Table A75. Post-consumer waste carpets generally contain dirt, chemicals, and other contaminants, which, combined, typically account for approximately 30% of their weight (Mihut *et al.*, 2001). Based on the above, the composition of post-consumer waste carpets is detailed in Table A76.

**Table A74**

Average composition (by weight) of UK post-consumer carpet waste face-fibres.

|  |  |
| --- | --- |
| Face-fibre classification | Percentage (%) |
| Nylon | 17 |
| Mixed synthetics | 13 |
| Wool | 17 |
| Polypropylene | 54 |

Source: adapted from Bird (2014).

**Table A75**

Percentage composition (by weight) of polypropylene and SBR constructed carpet components.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Face fibre | 46 |
| Primary backing (polypropylene) | 6 |
| Secondary backing (polypropylene) | 4 |
| Adhesive (SBR and calcium carbonate) | 44 |

Source: adapted from Sotayo *et al.* (2015) and ICF International (2015).

**Table A76**

Percentage composition (by weight) of post-consumer waste carpets.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Dirt (contaminants) | 30 |
| Face fibre (nylon) | 5 |
| Face fibre (wool) | 4 |
| Face fibre (PP) | 17 |
| Face fibre (mixed synthetics – PET, nylon, PP, and PVC) | 5 |
| Carpet backing (PP) | 7 |
| Adhesive (SBR) | 6a |
| Adhesive (CaCO3) | 25a |

a Based on an assumed carpet adhesive composition of 80% limestone (CaCO3) and 20% SBR (ICF International, 2015).

### Recycling system description

The process of carpet recycling was modelled based on an carpet recycling facility located in Alnwick, Northumberland and operated by Blackwater Ltd. (WRAP, no date-a). At the facility, the delivered carpets are first manually sorted into synthetic and natural fibre batches, with contaminants (such as metals) separated and sent on for either recycling or disposal. The sorted and separated batches are then fed into a shredder, with the shredded fibres then conveyed to a baler. Following compaction and baling, the shredded fibres are transferred via forklift to a storage area. According to the facility operator, 50% of the accepted feedstock (synthetic fibres only) is then used in of equestrian surfaces, whilst the remaining 50% is used as a fuel (known as Carpet Derived Fuel [CDF]) that is typically exported to Europe and used in cement kilns, boilers, or incinerators (WRAP, no date-a). Inventory data for the processing of post-consumer waste carpets are detailed in Table A77.

Where waste carpets are recycled and used in equestrian surfacing it was assumed that they substitute for synthetic stabilisation fibres. Equestrian surface synthetic fibre additives typically comprise a combination of polyester, polypropylene, foam rubber, and polyurethane; although the exact composition varies considerably depending on the manufacturer and the clients’ requirements (Swedish Equestrian Federation and Swedish University of Agricultural Sciences (SLU), 2014). Due to the variability in the fibre composition, it was assumed that fibres derived from recycled waste carpets substitute for virgin polypropylene. Primary production data were sourced from the ILCD v3.0 database (“Polypropylene granulate (PP), production mix, at plant”) and are representative of average European conditions in the year 1999 (JRC, 2009).

**Table A77**

Inventory data for mechanical processing of one tonne of post-consumer waste carpets.

|  |  |  |
| --- | --- | --- |
|  | Unit | Quantity |
| Inputs  |  |  |
| Electricity | kWh  | 45a |
| Diesel | l | 0.6b |
|  |  |  |
| Outputs |  |  |
| CDF, to thermal treatment (EfW) | kg | 350 |
| Equestrian surface material (synthetic fibres) | kg | 350 |
| Rejects, to disposal (non-hazardous landfill) | kg | 300 |

Source: adapted from WRAP (no date-a).

a Calculated based on a reported annual expenditure on electricity of £4.20 t-1 and an electricity price of 8.804 p kWh-1 (based on the average price of electricity purchased by a small manufacturing industry enterprise in the UK in 2010) (DECC, 2012).

b Calculated based on a reported annual expenditure on diesel of £0.67 t-1 and a diesel price of £1.13 l-1 (based on the average UK retail price (including tax) of diesel for 2010) (Bolton, 2014).

## Other

### Summary

An overview of key technical parameters used to model other materials recycling is presented in Table A78.

**Table A78**

Summary of other materials recycling system parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Waste material type | Material loss (%) | Recycled material | Secondary product | Substituted primary product | Material quality loss (%) |
| Absorbent hygiene products | 93.7 | PP | PP granulate | PP granulate | 10 |
| PET | PET flakes | PET flakes | 10 |
| Fluff pulp | Testliner | Kraftliner | 10 |
| Wellenstoff | Semi-chemical fluting | 10 |

### Absorbent hygiene products

#### Material composition

It was assumed that absorbent hygiene products (AHPs) collected for recycling would be composed exclusively of nappies. The average composition of an average disposable nappy sold in the UK in the year 2006 is detailed in Table A79.

**Table A79**

Average UK disposable nappy composition.

|  |  |
| --- | --- |
| Component | Percentage (%) |
| Fluff pulp | 34.1 |
| Super absorbent polymer (SAP) | 32.4 |
| Polypropylene (PP) | 16.6 |
| Low-density polyethylene (LDPE) | 6.0 |
| Adhesives | 3.8 |
| Polyethylene terephthalate (PET)/polyester | 2.2 |
| Other | 4.8 |

Source: Aumônier *et al.* (2008).

The composition detailed in Table A79 was modified to represent a waste nappy; necessary to account for the mass of excreta disposed with the waste nappies. Based on the average number of nappies used by a child over the average two and a half year period of nappy use, 3,796 (Aumônier and Collins, 2005), the average weight of a nappy, 38.6 g, and the assumed mass of excreta deposited with nappies over the same two and a half year period, 727 kg, it was estimated that excreta (which is assumed to be 18% faeces and 82% urine) comprised 83.2% of total waste nappies on a wet weight basis (Aumônier *et al.*, 2008). The average UK waste disposable nappy composition, including excreta, is detailed in Table A80.

**Table A80**

Average UK waste disposable nappy composition, including excreta.

|  |  |
| --- | --- |
| Component | Percentage |
| Faeces | 15.0% |
| Urine | 68.2% |
| Fluff pulp | 5.7% |
| SAP | 5.4% |
| PP | 2.8% |
| LDPE | 1.0% |
| Adhesives | 0.6% |
| PET/polyester | 0.4% |
| Other | 0.8% |

Source: adapted from Aumônier *et al.* (2008).

### Recycling system description

Collected nappies are sent to a waste nappy recycling facility in the UK where they are sterilised, shredded, and sorted to separate the recyclable components (plastics and fibres, both of which are of a high quality), which are sent for reprocessing, from the biosolids, which are sent for treatment at a publically owned treatment works (POTW), and residuals, which are sent for disposal.

#### Nappy recycling (dismantlement)

The recycling of AHP waste (nappies) process was modelled based on the Knowaste West Bromwich nappy recycling facility (closed as of June 2013), as described by Freyberg (2012). The process involves the autoclaving of the waste feedstock to sterilise the material, commence separation of fibres and release moisture. Following this, the nappies are shredded and sorted to separate plastics and fibres from any contaminants. Plastics are then washed and granulised before being processed into flakes ready for transportation to a reprocessor. Fibres are baled and transported to a paper mill for application in cardboard manufacture. Biosolids are disposed via sewer pipes for treatment at a POTW (Freyberg, 2012). Primary data from the Kowaste plant were not available. Moisture loss during the autoclave process was based on data from a mechanical heat treatment facility used as a proxy (Stringfellow *et al.*, 2010). The mechanical shredding and sorting process was modelled using a paper shredding and sorting process as a proxy (see Section 3.1.1). Inventory data for the nappies recycling process are detailed in Table A81. Material loss rates of 5% and 30% were assumed for plastics and fibres, respectively (Ward, 2004).

**Table A81**

Inventory data for the recycling of one tonne of waste nappies.

|  |  |  |  |
| --- | --- | --- | --- |
|   | Unit | Quantity | Reference |
| *Autoclave* |
| Process parameters |
| Moisture loss | % | 16 | Stringfellow *et al.* (2010) |
|  |
| *Mechanical shredding and sorting* |
| Process parameters |
| Transfer coefficients |
| PP to recycling | t t-1 | 0.95 | Ward (2004) |
| PP to disposal | t t-1 | 0.05 | Ward (2004) |
| PET to recycling | t t-1 | 0.95 | Ward (2004) |
| PET to disposal | t t-1 | 0.05 | Ward (2004) |
| Fluff pulp to recycling | t t-1 | 0.7 | Ward (2004) |
| Fluff pulp to disposal | t t-1 | 0.3 | Ward (2004) |
| Biowaste (excreta) to wastewater treatment | t t-1 | 1 | - |
| Other (SAP, adhesives & other) to disposal | t t-1 | 1 | - |

#### Recovered material recycling

Recovered fluff pulp was assumed to be sent to a recycled cardboard base paper production facility. Details of the reprocessing and market substitution are outlined in Section 3.5.2. Recovered PET and PP were assumed to be sent to polymer-specific recycling facilities. PET was assumed to be sent to a PET recycling facility where it would be reprocessed into secondary PET flakes (detailed in Section 5.5), whilst recovered PP was assumed to be sent to a PP recycling facility for use in the production of secondary PP pellets. Due to a lack of more specific data, HDPE recycling was used as a proxy for PP recycling (detailed in Section 5.6). Secondary PP pellets were assumed to substitute for primary PP pellets at a ratio of 1:1 (w/w). Primary production data were sourced from the ELCD 2.0 database (“*polypropylene granulate (PP), production mix, at plant*”) and are representative of average European conditions in the year 1999 (JRC, 2009). The process includes the transportation and use of energy and material inputs and the production of secondary PP pellets.

## Waste material characteristics

In order to model the various material recycling systems in EASETECH, waste materials had to be converted into one of the 48 material fractions used in EASETECH. Details of the waste material conversions used are presented in Table A82.

**Table A82**

Name of EASETECH material fraction used to describe modelled waste material types.

| Waste material component | EASETECH material fraction name |
| --- | --- |
| Green glass | Green glass |
| Brown glass | Brown glass |
| Clear glass | Clear glass |
| Other glass | Recyclable glass |
| Newspapers | Newsprints |
| Card | Other clean cardboard |
| Books | Books, phone books |
| Magazines | Magazines |
| Other paper | Other clean paper |
| Yellow pages | Books, phone books |
| Steel | Food cans (tinplate/steel) |
| Aluminium | Beverage cans (aluminium) |
| Oher plastic packaging | Hard plastic |
| Other plastic non-packaging | Hard plastic |
| PET bottles | Plastic bottles |
| HDPE bottles | Plastic bottles |
| Other plastic bottles | Plastic bottles |
| Expanded polystyrene (EPS) | Hard plastic |
| PVC | Hard plastic |
| Plastic film | Soft plastic |
| PP | Hard plastic |
| Other combustibles | Other combustibles |
| Wood | Wood |
| Ferrous metals | Food cans (tinplate/steel) |
| Non-ferrous metals | Beverage cans (aluminium) |
| Printed wiring board (PWB) | Other non-combustibles |
| Other | Other non-combustibles |
| Batteries | Batteries |
| Copper | Other metals |
| Other metals | Other metals |
| Plastics | Hard plastic |
| Cable | Other metals (66%); hard plastic (34%) |
| CRT glass | Non-recyclable glass |
| Glass | Non-recyclable glass |
| Automotive batteriesa | Batteries |
| Post-consumer, non-automotive batteriesa | Batteries |
| Crumb rubber | Rubber |
| Fibre & scrap | Textiles |
| Rubble (stones) | Stones, concrete |
| Soil | Soil |
| Gypsum | Stones, concrete |
| Lining paper | Other clean paper |
| Vegetable oil | Vegetable food waste |
| Mineral oil | Vegetable food waste |
| Paperboard | Other clean paper |
| Plastic (HDPE) | Hard plastic |
| Waterb | - |
| Organic material (hydrocarbons) | Other combustibles |
| Inert material (ash) | Ash |
| Textiles | Textiles |
| Shoes | Shoes, leather |
| Paper | Other clean paper |
| Dense plastic | Hard plastic |
| Dirt (contaminants)c | - |
| Face fibre (nylon) | Hard plastic |
| Face fibre (wool) | Textiles |
| Face fibre (PP) | Hard plastic |
| Face fibre (mixed synthetics – PET, nylon, PP, and PVC) | Hard plastic |
| Carpet backing (PP) | Hard plastic |
| Adhesive (SBR) | Rubber |
| Adhesive (CaCO3) | Other non-combustibles |
| Urine | Vegetable food waste |
| Faeces | Vegetable food waste |
| Fluff pulp | Other clean paper |
| SAP | Other combustibles |
| PP | Hard plastic |
| Adhesives | Other combustibles |
| PET | Hard plastic |
| LDPE | Soft plastic |
| Otherd | Other combustibles |

aModelled at the waste material type level, not the component level.

bModelled using a user-defined material fraction type comprising 100% water only.

cModelled using fractional composition data for “fine material” from Department of the Environment (1994b); Department of the Environment (1994a); Department of the Environment (1994c).

dOnly used to model AHP recycling.

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