ANALYSIS OF THE BENEFITS OF THE POST-SHREDDER RECYCLING CHAIN

Peter Vos, Steven De Meester & Jo Dewulf

The Policy Research Centre for Sustainable Materials Management brings together five renowned knowledge institutes: KU Leuven, Universiteit Antwerpen, Universiteit Gent, Universiteit Hasselt and VITO.

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For more information steven.demeester@ugent.be

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List of abbreviations

CEENE Cumulative Exergy Extraction from the Natural Environment

ELV End-of-Live Vehicles

ER_{cov} Energy Recoverability Benefit Rate

EU European Union

GDP Gross Domestic Product

LCA Life Cycle Assessment

LTRB Ligne pour le Traitement du Résidu de Broyage

MFA Material Flow Analysis

PCB Printed Circuit Board

PGM Platinum Group Metal

PST Post-Shredder Technologies

R'_{cyc} Recyclability Benefit Rate

RCR Recycling Rate

RVR Recovery Rate

WEEE Waste Electrical and Electronic Equipment

WWTP Wastewater Treatment Plant

1 Introduction

During the industrial revolution, mankind found a way to produce more products in a faster and more efficient way. This led to an unprecedented growth in population and economy, followed by an exponential increasing rate of innovation.

During the last one hundred years, global population quadrupled to 7 billion and global GDP grew more then 20-fold (Maddison, 2001). As a result, consumption patterns changed radically to a demand of complex products, associated with an enormous resource extraction. From 1900 to 2005, the use of construction materials for example grew by a factor 34 and ores and industrial minerals with a factor 27 (Krausmann et al., 2009).

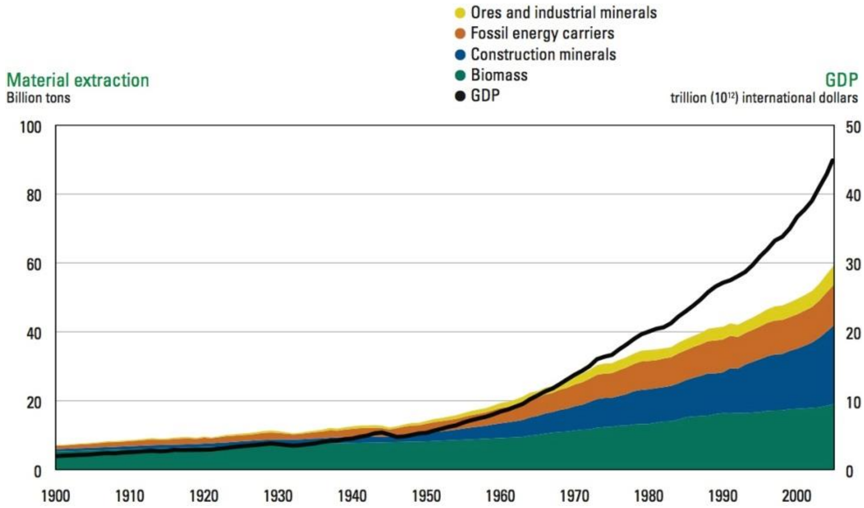

Figure 1: Global material extraction versus world Gross Domestic Product (GDP) (Krausmann et al., 2009)

This also results in high amounts of waste and because products are so complex, they are not easy to recycle. The created waste can be processed in different ways, and a waste hierarchy indicates which treatment is preferred above another. In general, waste should be avoided or reduced. This can be achieved by reducing the packaging size or the weight of the product. Since it is not always possible to reduce the amount of waste without a loss of quality, reusing the entire product as such is the second preferred scenario. Third, the focus is on recycling where new products are made from the disposed ones. It is possible to produce the same product or a totally different one, depending on the composition of the material, the quality and the way of disposal. When the quality or composition inhibits recycling, it is possible to recover a part of the original value in incineration. The material itself is lost, but the organic content is oxidised and energy is generated. The inorganic fraction will end up in the solid residue without giving energy and in general only allowing a lower application. The last option is landfilling, in which all materials are lost without any benefit.

The European Union acknowledges that waste can be an important resource in their report on critical raw materials (European Commission, 2014). Raw materials are of key importance for the economy, but are usually imported from other countries such as China. To lower our dependence on international suppliers, the European Commission identifies waste as one of the primary sources for these resources (European Commission, 2011). It is known that the presence of some (precious) metals in waste is several times higher than their concentration in natural ores (Betts, 2008). In theory, these metals have an unlimited recycling potential and can be recovered without a loss of quality (Gordon et al., 2006). Extracting secondary materials from waste does not only preserve our natural environment, it can also save huge amounts of energy. For example, secondary aluminium production requires 90-95% less energy compared to primary production (Cui & Forssberg, 2003).

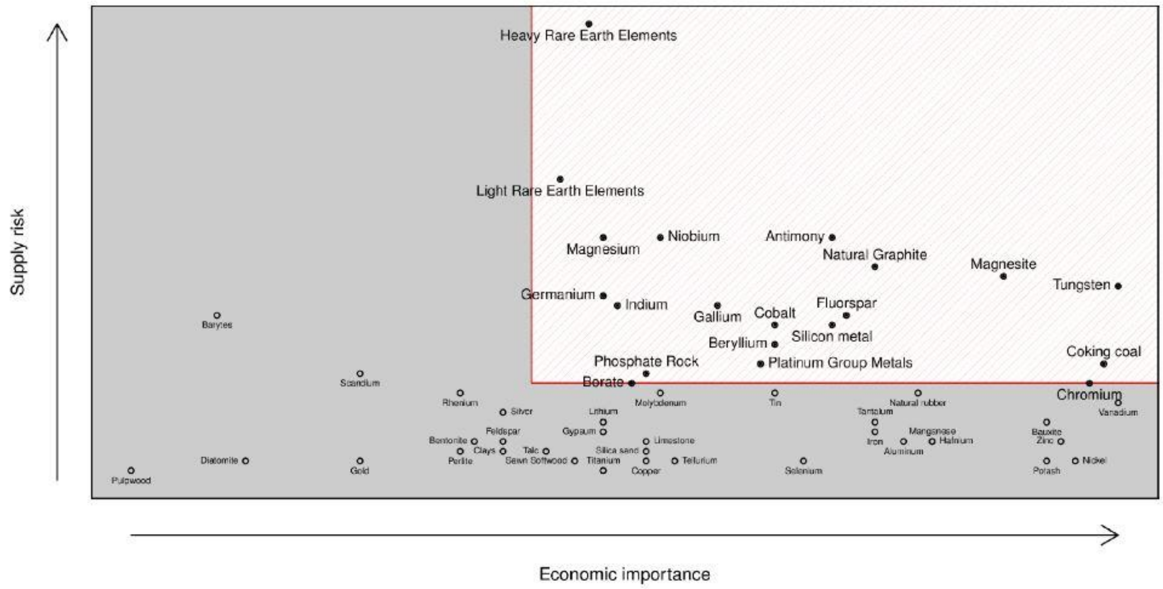

Figure 2: Identification of the EU critical raw materials, depending on the economic importance and the supply risk (European Commission, 2014)

The importance of recycling is well known in Flanders, which has a limited amount of virgin resources and where more than 70% of the waste is recycled (OVAM, 2015). This is only possible with an extensive collection and treatment system. Even complex waste streams like Waste Electric and Electronic Equipment (WEEE) are collected (115 585 tonnes in 2013) and processed with state-of-the-art technologies (Recupel, 2014). The recycling process generally starts by shredding the waste into small pieces, followed by a large number of Post-Shredder Technologies (PST).

These installations must meet strict regulations concerning emissions and amounts of materials to be recycled. The amount of material that can not be recovered is mostly landfilled and thus completely lost. Current technologies are not yet able to separate all fractions with a 100% recovery efficiency, so a certain loss is inevitable. For example, 85% of the mass of End of Life Vehicles (ELV) should be recycled and in total, 95% should be recovered in order to have less than of 5% going to landfill (European Commission, 2005). To ensure recycling is chosen over landfill, the government implies gate fees for the latter. Within recovery however, reuse, recycling and energy recovery are possible.

Even different recycling options are possible which can result in saving a certain number of resources. Therefore, it is very important to study and improve the recycling of all kinds of waste and to show the benefits of the possible recycling chains. This can be done in several ways. Frequently used methods are Material Flow Analysis (MFA) and Life Cycle Analysis (LCA). In MFA, the flow of materials is observed by making a mass balance, in order to identify process efficiencies and losses. LCA analyses the whole chain from resource extraction to end-of-life for its effect on the environment and provides a broader picture of the impact of a product of service. It also converts the inventory to a level of environmental impact. It can thus be used to identify the best way to process different kinds of waste. Bigum et al. (2012) used this approach to set up an inventory for the recycling and recovery of several metals such as copper, gold, nickel and palladium from Waste Electric and Electronic Equipment and to assess their environmental impact. The results show that the recovery of metals avoids an environmental impact, corresponding to savings both in material as in energy resources. Precious metals that are present in small quantities, such as gold, silver and palladium, generate high savings compared to other metals like copper and aluminium. In general, it was concluded that the recovery of metals from WEEE generates a significant environmental benefit. Another example is a study on the production of secondary metals, which shows that the primary production of a mix of metals including gold, platinum group metals, lead and nickel emits five times more carbon dioxide than their recycling processes (Hagelüken, 2008). This method is often used and very adequate to assess waste treatment options. In theory LCA/MFA are thus very attractive methods to give quantitative input to policy and industry on the different recovery scenarios. Both at product and at material level it is possible to compare the environmental effect of different scenarios. An example are the benefit rates developed by Ardente & Mathieux (2014), combining the benefits and costs of recycling a certain product to determine how much of the initional value can be recovered. The obtained benefit rate allows for a consistent and uniform comparison of different scenarios and allows to evaluate the potential of alternative techniques. This method was used by Debaveye et al. (2014) to compare different recycling scenarios for plastics in Flanders, resulting in a benefit rate of 78.2% for the recycling scenario and 39.4% for the energy recovery scenario. The fact that recycling has a benefit approximately twice as high as energy recovery could subsequently be used in policy making.

Van Eygen et al. (2015) performed a Material Flow Analysis and Life Cycle Assessment of laptop and desktop computers. He showed that the recovery of metals can still be improved. The analysis showed that, for example, 48.6% of all materials and 86.8% of recyclable metals present in a desktop computer are effectively recycled. Alltough the mechanical separation is of vital importance, an environmental impact analysis revealed that the subsequent recycling processes (e.g. secondary metal smelters) account for 96% of the environmental impact of the recycling chain.

Nevertheless, with 79% and 86% less resource consumption, the recycling of desktop and laptop computers performed significantly better compared to virgin production. On the other hand, for policy it would be easier to have environmental information of specific materials such as Fe, Pd, Cu etc. rather than on the product level. Therefore, this research aims at calculating the benefit of recycling at the level of specific material flows. Given the importance of the recycling processes also an in depth analysis of this recycling chain is made. The applicability of the method introduced by Ardente & Mathieux (2012) will be tested for different treatment options and material categories in order to improve the consistency of the results. The benefit rates of these materials will not only complete the information on the importance of recycling, but also a comparison with energy recovery will be made, allowing the identification of priority metals to be separated. As a result, a complete environmental assessment of specific materials present in shredder residues will be available as a single number expressing the benefit of the recovery scenario.

2 Objectives

The main objective of this study is to calculate the benefits for several material categories in shredder residues. For this purpose, materials present in shredder residue can be subdivided into 4 main categories: Metals, Precious metals, an inert fraction and a fibre-rich fraction. For each category, the aim is to investigate the final destination of the chosen products and the efficiency of these processing options. This gives a more complete picture compared to Debaveye et al. (2014) who studied solely plastic.

First, the materials to be analysed are selected within each category:

- Metals: nickel, lead, aluminium and copper
- Precious metals: silver, gold and palladium
- Inert fraction: sand and stones, iron oxide
- Fibre-rich fraction: car fluff

For every material, an estimation of the benefits of each end-of-life scenario will be made (recycling, energy recovery and landfill disposal). This will be done by calculating a benefit rate, as introduced by Ardente (2012). As a comparison is made between recycling and energy recovery, special attention will be given to materials that are non-combustible, as there is a gap in current research concerning the fate of these materials after incineration. Important differences between landfill and special ash-treatments will be quantified and implemented in the benefit rates.

This analysis will result in more complete information about the benefits of recycling not only the most important materials such as metals, but also about the lower-value streams such as fibres. With the inclusion of of lesser-known processes such as ash-treatment, a more complete analysis of the sustainability of recycling will be obtained. This can subsequently be used to compare and benchmark different strategies for reuse, recycling and recovery, which could potentially be used in policy.

3 Materials and methods

3.1 Scope

3.1.1 Functional unit

As mentioned before, it is of specific interest to have benefits and burden of recycling at the level of a specific material. Therefore the functional unit in this study is 1kg of pure material. So although in fact these materials occur in products with mixed compositions, we perform the analysis as a hypothetical scenario in which only 1kg of the pure material would be recycled. The materials analysed are nickel, lead, aluminium, copper, silver, gold, palladium, sand and stones, iron oxide (rust) and car fluff. To facilitate interpretation we have grouped them into 4 categories: metals, precious metals, an inert fraction and a fibre-rich fraction.

3.1.2 System boundaries

As this research investigates the end-of-life treatment of waste streams treated in a shredder, the analysis starts at the collection of waste and transport to the treatment facility. The processes before collection are considered as background processes. After passing through the dismantling, depollution, shredder and PSTs, the separated material is sent to the end-treatment for the production of secondary products.

Depending on the destination of the separated product, different scenarios are analysed. These scenarios include the production of the same product (e.g. secondary metal production) or other products (e.g. the use of slags as construction material) and energy recovery. Since there is no benefit related to landfill, only the impact thereof is considered. Figure 3 gives a general overview of the system boundaries.

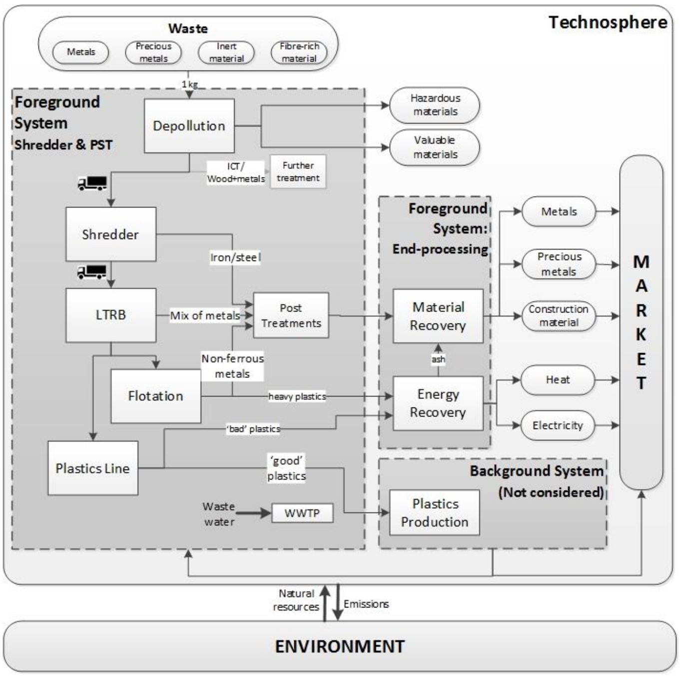

Figure 3: Overview of the system boundaries

3.2 Description of the Recycling processes

The whole treatment consists of a chain of complex processes. The foreground processes in this analysis are briefly discussed and are based on the Galloo plant in Menen, followed by different specific treatments. Data comes from direct contact with the company and is based on the recycling of laptops and desktop computers (Van Eygen et al., 2015). Other data sources are Belgian Scrap Terminal and literature.

3.2.1 Collection and sorting

The collection method is dependent on the type of waste. Waste Electric and Electronic Equipment (WEEE) is collected and sorted by the retailer or in a recycling park. Because of a diverse composition of waste in the shredder, a single distance was assumed for the transport of the collected waste. Transport was assumed to consist for 15% of fine transport and 85% of bulk transport, with a total distance of 60 km (Van Eygen et al., 2015).

3.2.2 Dismantling

A lot of products contain hazardous substances such as lubricants, batteries or mercury that have to be removed before being fed to the shredder. Other fractions are removed because of their high value, such as Printed Circuit Boards (PCBs) and capacitors. This pre-processing step is being done manually and it was assumed that no extra utilities are used here.

3.2.3 Mechanical separation and PST

The general treatment consists of four main treatment units. The waste is first sent to a large shredder where the material is comminuted into pieces smaller than 100 mm. These pieces are then sent to the different separation processes. First, they are separated in a light and heavy stream in a zig-zag separator. A magnet and an eddy current separate iron and aluminium from the light fraction. The heavy fraction undergoes handpicking and several magnets, mainly for copper removal.

After the shredder, the residues are sent to the LTRB (Ligne pour le Traitement du Résidu de Broyage) where organics and non-ferrous metals are separated. In the LTRB, a drum sieve separates the stream in a small (<35 mm) and large (> 35 mm) fraction. Dust is taken out by an air separator, the streams are washed and sent to a density separator. Chemicals are used as a density medium and cause the organics to float and the metals to sink. After a washing step, the density medium is recovered and residual ferrous metals are taken out by a magnet. Organics are sent to the Plastics Line and the non-ferrous metals are sent to the Flotation.

In the Flotation unit, to goal is to isolate the different non-ferrous metals. To achieve this, the stream goes through a drum sieve, two density separators, magnets, eddy currents and sieves. This complex system separates aluminium, printed circuit boards, cables, copper, stainless steel etc.

In the Plastics Line, organics are separated in 'good' and 'bad' plastics by a medium of 1.1 kg/L density. The 'good' plastics can be recycled in Galloo Plastics, the 'bad' plastics are sold as Refuse-Derived Fuel. Plastics will not be discussed here, as the benefit of plastics recycling was already investigated previously (Debaveye et al., 2014).

Apart from these four main treatments, there are several smaller post-treatments that are used to enrich or clean a stream to be sold for end-processing. These post-treatments include a smaller shredder (Eldan), a vibrating screen separator (Vibrosort), an optical sorting and a sieve drum. After the final treatment, every fraction is sold to a specific end-processing where secondary products are produced according to the material's quality.

Although the Galloo plant does not separate a fibre-rich fraction, the recovery of this fraction is done in a similar way. This stream mostly consists of car fluff, a light fraction coming from car seats and can be recovered with a high efficiency (Quidousse, 2015).

3.2.4 Incineration and ash-treatment

Ash treatment is important in the scenario where (precious) metals end up in a hazardous waste incineration plant. During incineration, a part of the metals ends up in the bottom ash fraction and thus, it might be possible to recover them. Although the recovery of metals from ashes is quite new and they usually occur in the very fine fraction due to their use as fine coatings, Flanders is enforcing its front runner position in recycling with specialised plants for ash treatment. Depending on the incineration facility, the ashes are first treated in the incineration plant itself with magnets and eddy currents. The remaining fraction is then sent to an ash treatment facility, such as Valormet in Moen or Valomac in Grimbergen. This treatment is based on size separation followed by magnetic and eddy-current treatment.

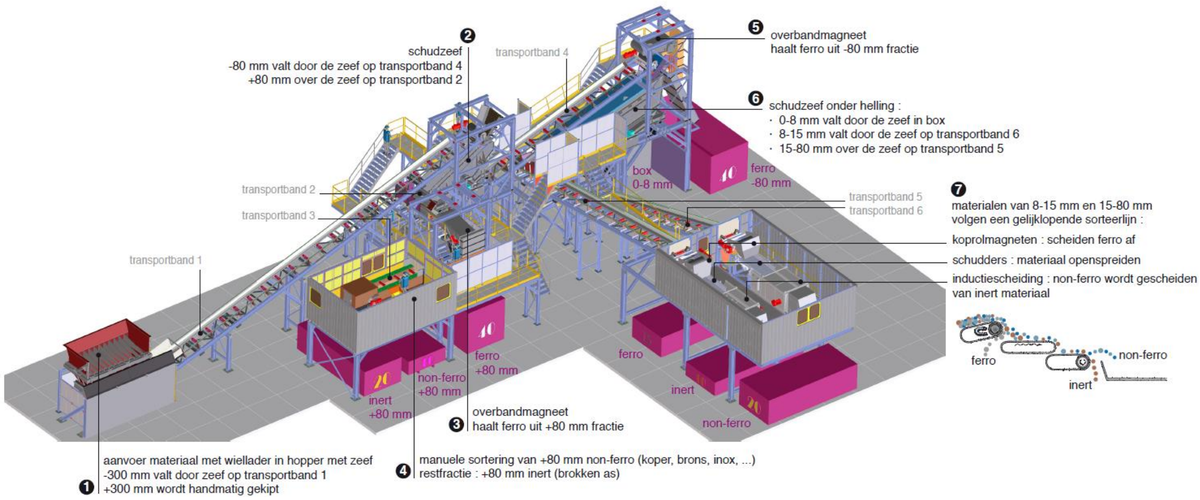

Figure 4: Scheme of the ash treatment facility of Valormet (Belgian Waste-2-Energy, 2014)

The ferro-fraction can be separated, and the other metals are isolated as a mix. This mix goes back to the mechanical separation plant for further treatment. Apart from the losses during incineration and first treatments, the recovery of metals in the mechanical treatment plant is assumed to be as efficient as for other incoming streams. Since the smallest fraction is not treated, literature and expert knowledge were used to estimate the size distribution of the different metals in the bottom ash fraction. The non-recovered fraction is used as construction material.

3.2.5 End-processing

The end-processing is specific for each material and will therefore be discussed individually.

3.2.5.1 Metals and precious metals

The most important metals like iron, stainless steel, aluminium and copper are separated and sent to a specific valorisation pathway, while the non-ferrous metals fraction is separated as a mix and sent to the precious metals smelter of Umicore, one of the only smelters in the world entirely working with secondary resources. The complex incoming stream is first melted at 1 200 °C, resulting in a liquid copper phase containing precious metals and a lead slag phase which contains most other metals. The copper phase goes to the leach-electro-winning plant and the lead slag goes to the blast furnace where other metallurgical processes guarantee a high recovery of metals (Hageluken, 2005).

Most of the lead, nickel, silver, gold and palladium are treated here. The minor part that cannot be recovered ends up in the slag phase and is used as construction material. Copper can be recovered here or in a copper smelter where it can be refined up to 99.99% purity. A part of the copper present in cables is sent to China and is recycled there.

The recovered aluminium is sent to a specialised aluminium smelter. A minor part is treated in China, where the manual separation of highly mixed waste streams is economically feasible. The scrap metal is melted, further refined and cast into a new form. Impurities end up in the slag phase that is used as construction material. The production of secondary aluminium saves 90-95% of energy compared to virgin production and is done without any quality loss of the material (Cui & Forssberg, 2003).

3.2.5.2 Fibre-rich fraction

In the past, the recovered fibres were used as a sludge stabilizing agent in wastewater treatment plants, thereby replacing polyelectrolytes. Nowadays, the entire fibre-rich fraction is sent to an incineration plant. Car fluff has an average heating value of 20 MJ per kg and is therefore well suited for this purpose (Santini et al., 2011; Vermeulen et al., 2011). Incineration plants must fulfil strict environmental regulations and are operated with different post-treatment techniques for the flue gases and solid residues. It was assumed that bottom ashes coming from the incineration of the fibre-rich fraction can be used as construction material without further treatment. If the ashes contain high amounts of (leachable) metals, further treatment is required.

Research is being done to find a better destination for this fibre-rich fraction. It is possible to obtain a strong and water-resistant plate material by treating the car fluff under high pressure and temperature (ARN, 2011). Because no data could be provided, this option will not be discussed.

3.2.5.3 Inert material

The composition of the inert fraction depends on its origin. It mostly consists out of sand and stones. If necessary, this fraction is treated in a hammer mill to obtain a uniform size before being used as construction material. The inert fraction of other shredders contains a lot of iron oxide (rust), that can be used in cement production where it replaces other sources of iron (Quidousse, 2015).

3.2.6 Transport

Transport of the materials to their concerning end-treatment cannot be neglected, as the specific treatment facilities are often located in other countries. Table 1 gives an overview of the assumed transport distances to the concerning end-treatments. These distances concern transport from and to Galloo, but are assumed to be representative for other facilities as well.

Table 1: Overview of the transport distance from the mechanical separation plant to the final treatment

Destination	Distance	
Aluminium smelter	1 217	km
Integrated smelter	118	km
China: road to harbour	69.6	km
China: naval	18 470	km
Copper smelter	154	km
Incineration plant	134	km
Incineration to ash-treatment	112	km
Ash-treatment to mechanical separation	35	km
Inert material: Imog	31.2	km
Wastewater treatment plant	216	km

3.3 Life Cycle Inventory

3.3.1 Mechanical separation and PST

In order to calculate the recycling rate and recovery rate, the flow of materials through the recycling chain has to be known. An extensive analysis of the Galloo plant was performed by Van Eygen et al. (2015) and could be used to estimate the use of utilities and the recovery efficiency of metals in the system. These data were completed with data from literature (Bigum et al., 2012; Cui & Zhang, 2008; Gmünder, 2007; Huisman, 2003; UNEP, 2013). Since the input in the mechanical separation plant is variable, the flow of metals in the system is changing constantly.

Therefore, the use of utilities of the mechanical separation plant was allocated to the materials on a mass basis, using the yearly consumption of a certain utility and the average mass throughput. It was thus assumed that 1 kg of aluminium in the PST requires the same amount of utilities as 1 kg of gold or inert material, as the plant operates as a whole and not for the recovery of 1 specific material.

3.3.2 Incineration and ash treatment

The recovery of metals from incineration residues is quite new and therefore, information about the behaviour of metals during incineration and their partitioning in the different waste streams was needed. An extensive literature search showed that most of the metals (85% on average) end up in the bottom ashes and a minimum of 10-15% is lost in the flue gases or fly ashes. Lead has a slightly different behaviour due to its higher volatility, and an average of 66% ends up in the bottom ashes (Belevi, 2000; Biganzoli et al., 2014; Morf et al., 2000; Morf et al., 2013; Phongphiphat et al., 2011; Sorum et al., n.d.; Yao et al., 2010; Zhang., 1999). Oxidation of the metals is also possible, but since the effect of metal oxidation on the recoverability is not known, this was not further taken into account. Although most of the metals end up in the bottom ash fraction, the larger part is present in the fraction smaller than 8mm and cannot be treated for metal recovery. Literature shows that pure nickel and precious metals have a recovery of less than 5% because of their use as thin coatings. Aluminium and copper usually have a higher recovery of 17% and 25% (Berkhout, 2011; Born, 2014; De Vries, 2009; Grönholm, 2014; Kallesoe, 2014; Koralewska, 2014; Quicker, 2014; Schunicht, 2014). Other information about the ash treatment facilities was provided by Galloo and Valormet.

3.3.3 Secondary material production

Basic data about the efficiency of secondary material production was provided by Van Eygen (2014) for the selected metals, precious metals and sand and stones. Missing data was completed by expert knowledge and literature. In general, the production of secondary metals has a high performance with efficiencies above 90% for all the selected metals. The use of slags, sand and stones as construction material has a 1:1 replacement factor. The use of iron oxide in cement production does not need any further treatment and replaces the same amount of iron oxide from other sources.

3.3.4 Fibre-rich fraction

Car fluff can be used as a sludge stabilizing agent, thus avoiding the use of other stabilizing agents. The fibre-rich fraction can be used without further treatment, as the stabilised sludge is sent to an incineration facility (Quidousse, 2015).

The replacement factor for polyelectrolytes was calculated from literature and online product characteristics. Based on the amount of water that can be absorbed, a replacement factor of 0.5 kg of polyelectrolytes per kg of car fluff was determined (Aguilar et al., 2005; Ecosorb International, 2014; Quidousse, 2015).

3.4 Impact Assessment: Analysis of the Resource Efficiency

The determination of the environmental benefit requires the quantification of the impact of all related processes such as landfill disposal, virgin production and recycling processes. This quantification is done using the CEENE method. CEENE stands for Cumulative Exergy Extraction from the Natural Environment, and is a measure for the total amount of resources extracted from the environment (Dewulf et al., 2007). The impact is expressed in MJ exergy, which takes into account the quality of the resource, depending on the possibility to perform labour from differences in pressure, temperature or chemical composition in comparison with the environment (Dewulf & Van Langenhove, 2008).

This benefit can be expressed in different ways. In order to compare different materials with different destinations, a complete and uniform indicator is needed. Ardente et al. (2012) introduced a life cycle based indicator, taking into account the different benefits of a certain scenario, together with the environmental cost of the recycling processes. This net benefit is compared to the maximum obtainable benefit, corresponding with a 100% recycling rate. The calculation is based on the assumption that recycled products will avoid the production of virgin products, thus avoiding a certain negative impact.

As this project concerns the valorisation of shredder residues, the benefit of reducing the amount of waste or reusing the product as such is out of the scope of this research. Here, recycling is the preferred scenario.

3.4.1 Recyclability benefit rate

The recyclability benefit rate expresses the benefit obtained by making products out of secondary resources. The benefit rate as introduced by Ardente & Mathieux (2014) is calculated as follows:

$$R'_{cyc,n} = \frac{\sum_{i=1}^{P} m_{recyc,i} \cdot RCR_i \cdot D_{n,i} + \sum_{i=1}^{P} m_{recyc,i} \cdot RCR_i \cdot \left(k_i \cdot V_{n,i} - R_{n,i}\right)}{\sum_{i=1}^{P} m_i \cdot V_{n,i} + M_n + U_n + \sum_{i=1}^{P} m_i \cdot D_{n,i}} \cdot 100$$

Where:

$R'_{cyc,n}$ = Recyclability benefit rate for the n^{th} impact category [%]

m_i = mass of the i^{th} part of the product [kg]

$m_{recyc,i}$ = mass of the i^{th} part of the product that is actually recycled [kg]

RCR_i = Recycling rate of i^{th} part of the product, i.e. the percentage of the product that is undergoing a certain recycling process [%]

$D_{n,i}$ = impact related to the disposal (landfill) of the i^{th} part of the product [CEENE/kg]

k_i = downcycling factor. In this study: mass based [dimensionless]

$V_{n,i}$ = impact related to the virgin production of the i^{th} part of the product [CEENE/kg]

$R_{n,i}$ = impact related to the recycling of the i^{th} part of the product [CEENE/kg]

M_n = impact related to the manufacturing of the product [CEENE]

U_n = impact related to the use of the product [CEENE]

P = the amount of product parts

In this research, a slightly modified formula will be used, as the benefit is calculated for a material and not for a product. Since the input in a shredder is very complex and variable, it is not possible to attribute the impact to certain products. Therefore, the manufacturing and use phase will be neglected. The benefit will thus be subdivided into different destinations instead of different product parts. For the material downcycled as construction material, the approach from Huysman et al. (2015) was followed, but the 1:1 substitution rate for construction material enables the original formula to be used. The modified formula is as follows:

$$R'_{cyc,n} = \frac{\sum_{i=1}^{P} m_{recyc,i} \cdot RCR_i \cdot \left(D_{n,i} + k_i \cdot V_{n,i} - R_{n,i}\right)}{\sum_{i=1}^{P} m_i \cdot \left(V_{n,i} + D_{n,i}\right)} \cdot 100$$

3.4.2 Energy recoverability benefit rate

The Energy recoverability benefit rate expresses the benefit obtained by the incineration and subsequent energy production of a certain product or material. With this generated energy, the production of electricity and heat by other sources, such as fossil fuels, is avoided.

$$ER_{cov,n} = \frac{\left(\eta_{el} \cdot \sum_{i=1}^{P} RVR_i \cdot m_{recov,i} \cdot HV_i\right) \cdot El_n + \left(\eta_{heat} \cdot \sum_{i=1}^{P} RVR_i \cdot m_{recov,i} \cdot HV_i\right) \cdot Heat_n - \sum_{i=1}^{P} m_{recov,i} \cdot I_{i,n}}{\sum_{i=1}^{P} m_i \cdot V_{n,i} + M_n + U_n + \sum_{i=1}^{P} m_i \cdot D_{n,i}} \cdot 100$$

Where:

$ER_{cov,n}$ = Energy recoverability benefit rate for the n^th impact category [%]

η_{el} and η_{heat} = Average production efficiency of electricity and heat, assumed to be 30% and 0% [%]

RVR_i = Recovery rate of the i^th part of the product that is sent to energy recovery [%]

$m_{recov,i}$ = mass of the i^th part of the product that is sent to energy recovery [kg]

m_i = the mass of the i^th part of the product [kg]

HV_i = Heating value of the i^th part of the product that is sent to energy recovery [MJ/kg]

El_n = Average impact related to the production of electricity [CEENE/MJ]

$Heat_n$ = Average impact related to the production of heat [CEENE/MJ]

$I_{i,n}$ = Average impact of the incineration of the i^th part of the product [CEENE/kg]

$V_{n,i}$ = Average impact due to the virgin production of the i^th part of the product [CEENE/kg]

M_n = Average impact due to the manufacturing of the product [CEENE]

U_n = Average impact due to the use of the product [CEENE]

$D_{n,i}$ = Average impact due to the disposal of the i^th part of the product [CEENE/kg]

P = the amount of parts in the product

Although this formula is very useful to express the benefit of combustible materials, it does not include the avoided landfill disposal or the fate of non-combustible materials, such as the use of bottom ash as construction material. Therefore, the formula was modified to be better suited for the goal of this study. Terms were added to express the benefit of the avoided landfill disposal of the product, the avoided virgin production (e.g. the use of bottom ash as construction material) and the cost of the recycling processes before and after the incineration. Since the use of heat is almost non-existing in Flanders, this term was neglected.

$$ER_{cov,n} = \frac{\sum_{i=1}^{P} m_i \cdot RVR_i \cdot D_{n,i} + \left(\eta_{el} \cdot \sum_{i=1}^{P} RVR_i \cdot m_{recov,i} \cdot HV_i\right) \cdot El_n + \sum_{i=1}^{P} m_i RVR_i (k_i \cdot V_{n,i} - I_{n,i} - R_{n,i})}{V_n + D_n} \cdot 100$$

Where the new factors are:

$D_{n,i}$ = Average impact related to the landfill disposal of the material having the ith destination [CEENE/kg]

D_n = Average impact related to the landfill disposal of 1 kg of material [CEENE]

k_i = downcycling factor for the material being downcycled into material i [dimensionless]

$V_{n,i}$ = Average impact related to the virgin production of the secondary material obtained by valorising the bottom ashes [CEENE/kg]

V_n = Average impact related to the virgin production of 1 kg of original material [CEENE]

$R_{n,i}$ = Average impact due to the recycling of the bottom ashes into material i [CEENE/kg]

This formula gives a more complete quantification of the benefit obtained by sending a certain material to an energy recovery facility, since it cannot be assumed that the solid residue is landfilled without any further treatment. Depending on the treatment of the ashes, the avoided virgin products are metals or construction material. In the case of metal recovery, the part that could not be recovered was still used as construction material.

3.5 Scenarios

Because the analysed system is a complex chain of processes, different scenarios will be analysed in order to get a complete image of the actual environmental benefits. For all material categories, a recycling scenario will be compared with an energy recovery scenario. The concerning recycling scenario is clear: we assume that the material is recycled into the same quality material or downcycled as a product with lower quality, such as construction material. In the energy recovery scenario, the material is sent to an incineration plant. The combustion of organic matter will result in electricity and heat production while inorganic materials will leave the facility in the bottom- or fly ash or the flue gas without any benefit. The bottom ash fraction can be treated to separate metals or can be used as construction material. As the recovery of metals from bottom ash is not yet common practise in Europe, a scenario with and without metal recovery was analysed within the energy recovery scenario. An inadequate separation (at home or at the treatment facility) can cause the metals to be sent to incineration, but this will never be done on purpose.

The recycling scenarios start at the mechanical separation plant. Two different scenarios are distinguished, containing the same processes but differing in point of view. In the first scenario, called 'Total treatment', the recovery efficiency of the shredder and PST is included in the overall recycling rate. The recycling rate of this scenario accounts for the losses at the mechanical separation plant and the end-processing. The second scenario, called 'Final treatment', does not account for losses during mechanical separation and only treats the amount of material that is actually sent to the final treatment. For example, if the shredder has a recovery of 50% and the final treatment an efficiency of 90%, scenario 1 will discuss 1 kg of material going through the shredder and PSTs, 0.5 kg material going to a useful treatment that produces 0.45 kg of secondary material. In the second scenario, 1 kg of material is sent to the final treatment for the production of 0.9 kg of secondary material. The Final Treatment scenario will not be discussed in the results but will be given in the appendix. Figure 5 displays an overview of the different scenarios.

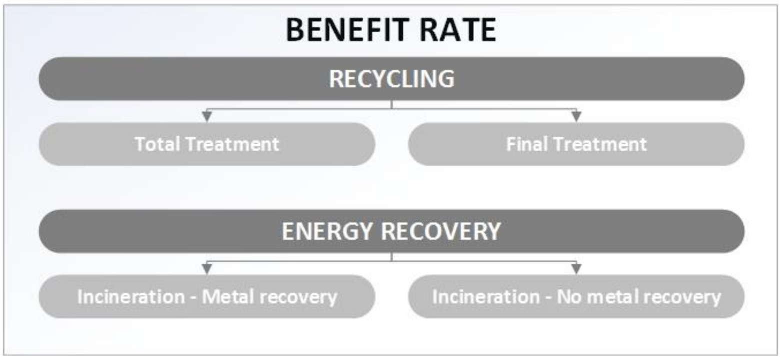

Figure 5: Overview of the different scenarios

As the recycling chain contains several different processes, the determination of the efficiency of every process is needed for the calculation of the benefit rates, as the recycling rate (RCR) and recovery rate (RVR) are a measure for the global efficiency throughout the whole chain. The rates are a multiplication of the efficiencies of every process, and as different scenarios are calculated, the rates can differ per scenario. Figure 6 illustrates the efficiencies taken into account for the different scenarios.

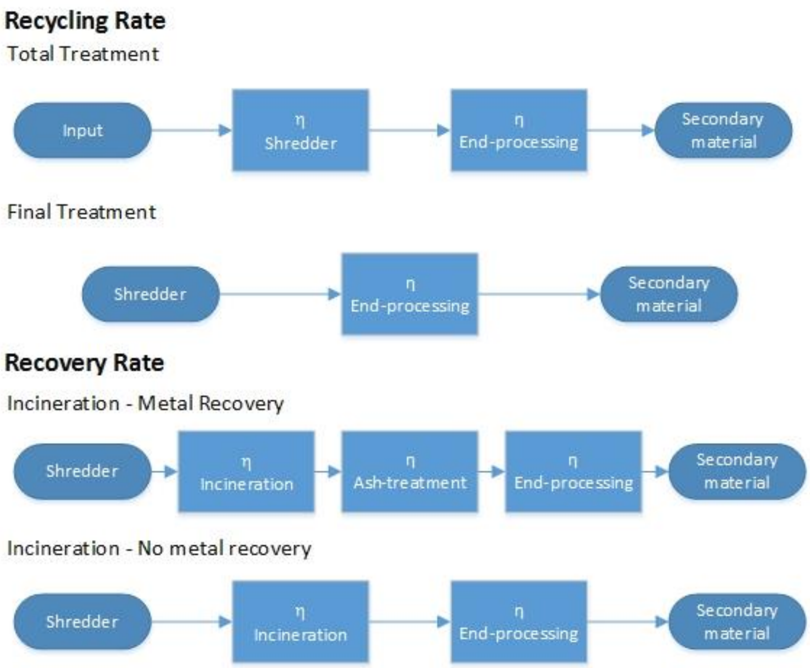

Figure 6: Illustration of the determination of the Recycling rates and Recovery rates for the different scenarios. Values can differ in every scenario

Efficiencies with the same name do not necessarily have the same value. The 'end-processing' efficiency of the metal recovery scenario for example differs from the one without metal recovery. In addition, it should be noted that the efficiencies in this figure can be further subdivided. The efficiency of the shredder is a combination of the efficiency of the manual dismantling, shredder and PSTs, and the efficiency of the ash-treatment is a combination of the treatments in companies like Valormet and Galloo.

All of these scenarios will have a certain benefit rate and will be compared with eachother. By comparing recycling with energy recovery, a preferred scenario can be identified for different material categories. Debaveye et al. (2014) made a comparison for plastics by calculating the ratio of the recyclability benefit rate and the energy recoverability benefit rate. The same approach was used in this study. Although, it has to be stated that only the fibre-rich fraction is suited for energy recovery. Other materials, such as metals or the inert fraction, end up in the solid residues and do not deliver energy. Whether or not these residues are given a further treatment for material recovery, the ratio will be a comparison of two recycling scenarios and should therefore be interpreted with care.

3.6 Sensitivity Analysis

Next to the normal benefit, a sensitivity analysis was performed to analyse the influence of the criticality of materials. The recovery of certain metals is more important because of its economic importance or its supply risk. Because this criticality is mostly related to the virgin material, the impact of virgin production was given an extra weight C, as shown below.

$$R'_{cyc,crit,n} = \frac{\sum_{i=1}^{P} m_{recyc,i} \cdot RCR_i \cdot \left(D_{n,i} + k_i \cdot C \cdot V_{n,i} - R_{n,i}\right)}{\sum_{i=1}^{P} m_i \cdot \left(C \cdot V_{n,i} + D_{n,i}\right)} \cdot 100$$

$$ER_{cov,n} = \frac{\sum_{i=1}^{P} m_i \cdot RVR_i \cdot D_{n,i} + \left(\eta_{el} \cdot \sum_{i=1}^{P} RVR_i \cdot m_{recov,i} \cdot HV_i\right) \cdot El_n + \sum_{i=1}^{P} m_i RVR_i (k_i \cdot C \cdot V_{n,i} - I_{n,i} - R_{n,i})}{C \cdot V_n + D_n} \cdot 100$$

With

C = the criticality of the material, as calculated in the criticality report (European Commission, 2014).

Table 2 gives an overview of the criticality of the selected metals. As lead was not analysed for its criticality by the European Commission, no value could be obtained and no criticality weighting could be performed for this metal. For palladium, the criticality of Platinum Group Metals was used and for iron oxide, the value for iron ore was used.

Table 2: Criticality values for the selected materials (European Commission, 2014)

Material	Criticality (C)
Nickel	2.12
Lead	/
Aluminium	3.26
Copper	1.27
Silver	3.48
Gold	0.57
Palladium	7.76
Iron oxide	3.7

3.7 Assumptions

The modelling of industrial processes always comes with some uncertainty because of limited data availability. Therefore, it is necessary to make some assumptions about certain processes and flows. Assumptions are usually based on literature and expert knowledge.

- Data from the Galloo mechanical separation plant the main data source and this is thus not necessarily the ‘average’ plant.
- For the analysis of nickel, only pure nickel flows were analysed. Nickel present in steel was not taken into account, as it is an inherent part of the steel and no secondary nickel can be produced from steel scrap.
- It was assumed that metals that are not sent to a specialised treatment are lost in landfill or transferred to a slag phase.
- The use of slags as construction material was only assumed for destinations that specifically state to valorise the slag phase. If no specific information was provided, the residue was assumed to be landfilled.
- It was assumed that for the metal recovery scenario, all metals present in the bottom ash that do not end up in the mechanical separation plant are used as construction material.
- The fibre-rich fraction was assumed to have a composition of 50% polyurethane foam, 25% of polypropylene fibres and 25% of PET-fibres (Quidousse, 2015).
- No information was found on the transfer of inert materials to the different incineration residues. Therefore, it was assumed that inert materials such as sand and stones are entirely transferred to the bottom ash phase.
- It was assumed that in the incineration scenario with metal recovery, no copper is sent to China. In the incineration, the plastic coating is burned, allowing the copper to be recovered more easily. As a result, no special cable treatment is needed anymore.

4 Results and discussion

The next sections will discuss the results obtained for the different scenarios. Four scenarios were analysed (see section 3.5) accounting for different treatments and points of view. In every scenario, a normal benefit rate and a criticality weighted benefit rate was determined. For simplicity, the results from the 'final treatment'-scenario will not be displayed here, but will be given in the appendix. In general, the results show the same trends as the Total Treatment scenario.

4.1 Recycling Rate (RCR)

Based on available data, literature and experts, efficiencies for every process could be determined. Table 3 displays the results, taking into account the different destinations of all the materials, the use of slag residues as construction material and losses. Individual process efficiencies can be found in the appendix. A visual illustration of the material flow is given in Figure 7 for metals and precious metals and in Figure 8 for the inert and fibre-rich fraction. Losses are going to landfill.

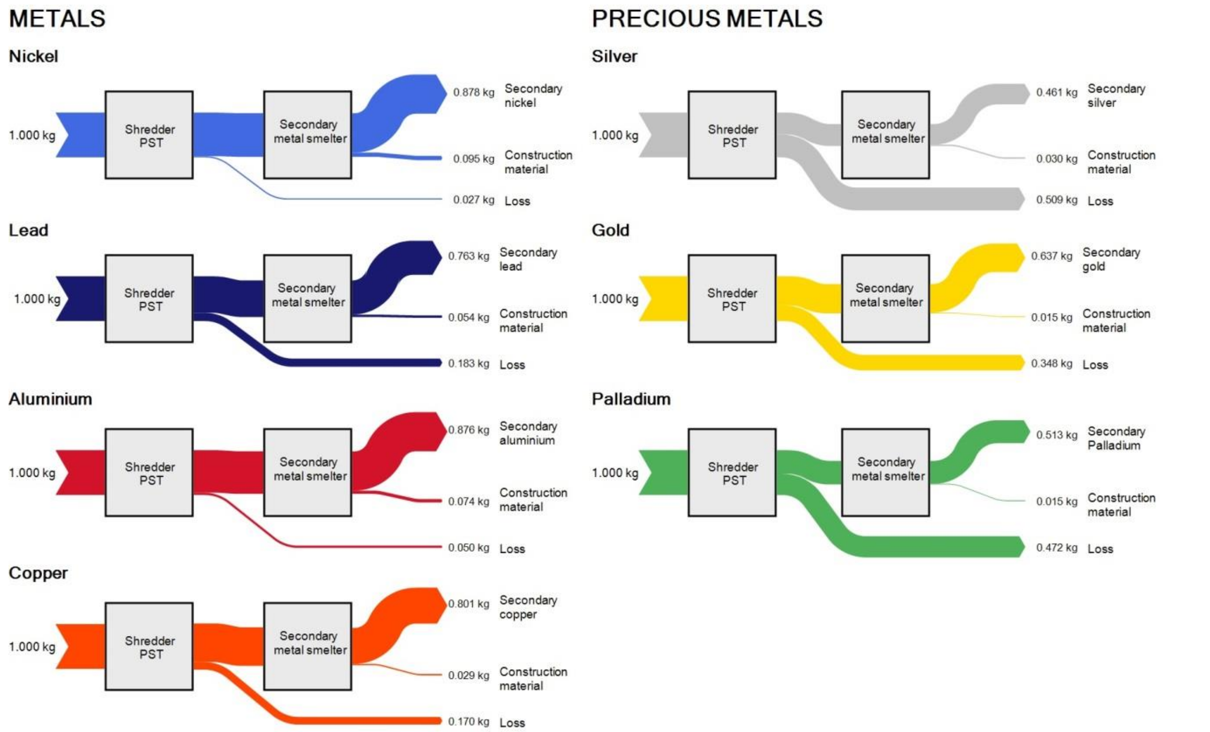

Figure 7: Material flow of the Total Treatment scenario for metals and precious metals

Figure 8: Material flow of the Total Treatment scenario for the inert and fibre-rich fraction

From the table we can conclude that the general recycling rate for metals is quite high. This means that both the mechanical separation plant and the secondary metal production is performant. The mechanical separation of precious metals has a quite low efficiency and causes a lot of losses, as can be seen in the figures above. This low separation is caused by the occurrence of these metals in the waste stream: they are mostly applied as a very thin coating on printed circuit boards of electronic devices and are easily lost during shredding and sieving. On the other hand, this loss is partially compensated in the integrated smelter, which has an efficiency of almost 100% for precious metals.

Table 3: Recycling rates (RCR) for the Total Chain and End-processing scenario

Material	**Destination**	**RCR Total Treatment**
Metals		$\eta_{shredder} \cdot \eta_{end\text{-}processing}$
Nickel	Secondary nickel	87.75%
	Construction material	9.5%
Lead	Secondary lead	76.25%
	Construction material	5%
Aluminium	Secondary aluminium	83%
	Secondary aluminium (China)	5%
	Construction material (Aluminium smelter)	5%
	Construction material (Umicore)	3%
Copper	Secondary copper	79%
	Secondary copper (China)	2%
	Construction material	3%
Precious metals		
Silver	Secondary silver	46%
	Construction material	3%
Gold	Secondary gold	64%
	Construction material	1%
Palladium	Secondary palladium	51%
	Construction material	2%
Inert material		
Sand and stones	Construction material	48%
Iron oxide	Cement production	100%
Fibre-rich fraction		
Car fluff	Sludge stabilisation	100%

The recycling rate of sand and stones is also quite low. Some hazardous substances can occur in these flows, making for a safe valorisation impossible. All of the iron oxide (rust) and car fluff is recovered, as they are more a waste fraction then a key product to be separated. The processing of these streams is not a primary objective of the mechanical separation plant but raises the total benefit of the plant.

4.2 Recovery Rate (RVR)

The recovery rate represents the amount of material that is incinerated and subsequently recovered from the bottom ashes or used as construction material. More information about the determination of the recovery rate was provided in section 3.4.2. Figure 9, Figure 10 and Figure 11 show the material flow of the different materials, Table 4 gives the numerical recovery rates for the scenarios with and without metal recovery. Individual process efficiencies can be found in the appendix.

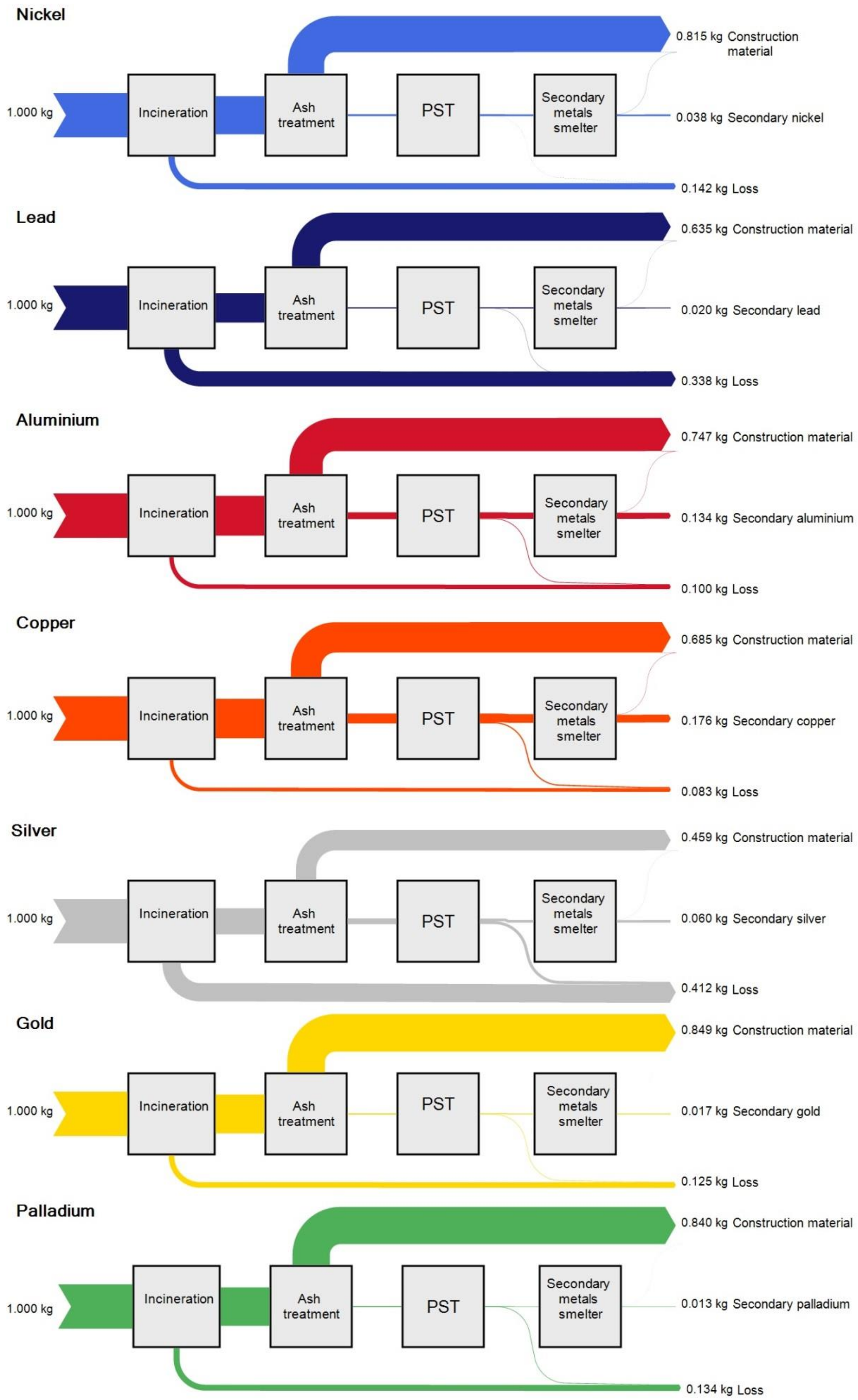

Figure 9: Material flow of the Energy Recovery scenario with Metal Recovery

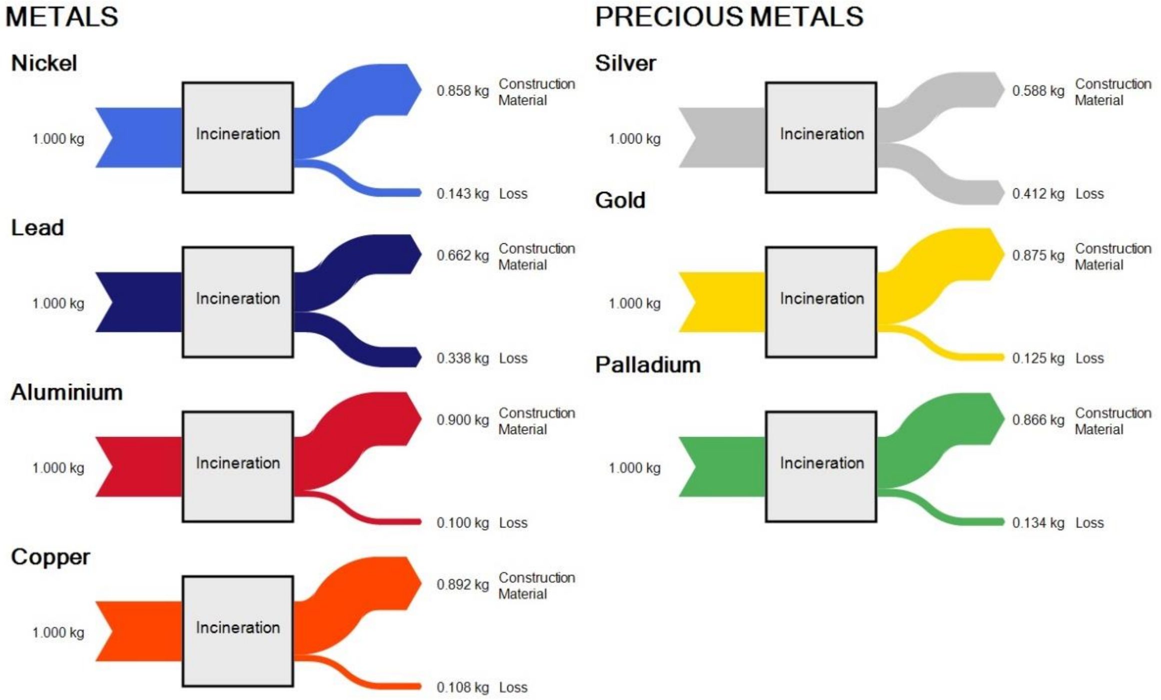

Figure 10: Material flow of the Energy Recovery scenario without metal recovery

Figure 11: Material flow in the Energy Recovery scenario for the inert and fibre-rich fraction

As previously explained, it was assumed that the entire fraction was sent to the incineration facility, as this reflects the scenario where no effort is put into an advanced separation of the materials. During combustion, part of the metals can be entrained in the flue gases, oxidise, volatilise or be lost in another way. Only the part that ends up in the bottom ash can be given a useful destination, losses are sent to landfill. Without metal recovery, the entire bottom ash fraction is used as construction material. If an ash treatment is performed, the bottom ashes are treated in different facilities and a part of the metals can be recovered and sent to metal smelters. The non-recovered part is again used as construction material. Obviously, no metals can be recovered from the inert fraction or the fibre-rich fraction.

The material flows in the figures above are easy to compare. In the incineration scenario with metal recovery, the amount of secondary metal production is low for all metals. The most important differences can be seen in the amount that is lost or used as construction material. There is no correlation within the material categories, as every metal behaves in a different way. The same conclusion can be made for the incineration scenario without metal recovery, where lead and silver have the biggest losses. Figure 11 shows that no inert material is lost while only a small fraction of the car fluff is used as construction material. This is due to the combustion with energy production; the 30% going to construction material represents the amount of ashes produced per kg of car fluff.

If the Recycling Rates in Table 3 are compared with the Recovery Rates in Table 4, it can be concluded that losses are always higher in the energy recovery scenario. This will have an influence on the Benefit rates, as they are proportional with the recycling and recovery rate.

Table 4: Recovery Rates (RVR) for Energy Recovery with and without metal recovery

Material	Destination	Recovery Rate (RVR)
Incineration - Metal Recovery		$\eta_{incineration} \cdot \eta_{ash\text{-}treatment} \cdot \eta_{end\text{-}processing}$
Metals		
Nickel	Secondary nickel	3.8%
	Construction material	96.1%
Lead	Secondary lead	2.0%
	Construction material	97.5%
Aluminium	Secondary aluminium	12.7%
	Secondary aluminium (China)	0.7%
	Construction material	86.5%
Copper	Secondary copper	17.6%
	Construction material	68.5%
Precious metals		
Silver	Secondary silver	6.0%
	Construction material	87.5%
Gold	Secondary gold	1.7%
	Construction material	97.4%
Palladium	Secondary palladium	1.3%
	Construction material	97.4%
Incineration - No metal recovery		$\eta_{incineration} \cdot \eta_{end\text{-}processing}$
Metals		
Nickel	Construction material	86%
Lead	Construction material	66%
Aluminium	Construction material	90%
Precious metals		
Silver	Construction material	59%
Gold	Construction material	88%
Palladium	Construction material	87%
Inert material		
Sand and stones	Construction material	100%
Iron oxide	Construction material	100%
Fibre-rich fraction		
Car fluff	Construction material	30%

4.3 Benefit Rates

Using the recycling rates and recovery rates obtained in 4.1 and 4.2 and the results from the environmental impact assessment of the different scenarios, the recyclability benefit rate and energy recoverability benefit rate could be calculated for all material categories. Because there are some important differences between different material categories, both the relative benefit rate and the absolute benefit in MJ exergy per kg of material will be given. The absolute benefit is the numerator of the relative formulas given in sections 3.4.1 and 3.4.2.

4.3.1 Recyclability Benefit Rate (R'_{cyc})

The Recyclability Benefit Rate expresses the benefit of a product entering the recycling chain instead of being sent to landfill. Every benefit above zero will result in a reduction of the global environmental impact compared to the production from virgin resources. Negative benefits indicate that the recycling processes itself have a higher environmental impact then the avoided virgin material. Since a negative benefit is not suited for further comparison, they are given a value of zero. Results are given in Table 5. The results of the Final Treatment scenario can be found in the appendix.

Table 5: Overview of the Recyclability Benefit Rates

	Total treatment RCR = $\eta_{shredder} \cdot \eta_{end\text{-}processing}$	
	Absolute Benefit [MJex/kg]	Relative Benefit Rate
Metals		
Nickel	216.5	81.9%
Lead	24.7	72.7%
Aluminium	164.8	75.4%
Copper	86.4	79.2%
Precious metals		
Silver	679.5	42.2%
Gold	253779.6	62.4%
Palladium	106178.8	50.3%
Inert fraction		
Sand and stones	0	0%
Iron oxide	0.26	17.0%
Fibre-rich fraction		
Car fluff	20.7	34.1%

Several remarks can be made here. The recyclability benefit rate in the total treatment scenario is remarkably higher for metals than for precious metals. On average, the benefit rate for metals is 77.2%, compared to an average benefit rate of 51.6% for precious metals. This difference can be explained by the lower separation efficiency of precious metals in the mechanical separation plant. The benefits of the final treatment scenario are higher, because only losses in the metal smelter are accounted for. Precious metals (92.3% on average) have a higher benefit rate than metals (87.3%), because they can be recovered very efficiently in an integrated smelter. A better primary separation of precious metals could thus significantly improve the benefit rate. If the absolute values of the benefits are compared, different conclusions can be made. The recycling of precious metals results in a very high benefit, with values up to 1000 times higher than for metals. On average, 976.4 kg of metals need to be recycled to have the same absolute environmental benefit as 1 kg of recycled precious metals. The metals nickel, lead and aluminium have an occurrence 350 times higher than precious metals (on average)(Van Eygen et al., 2015). This taken into account, the recycling of precious metals could generate a benefit almost three times as high as the other metals.

If we take a look at the benefit of the inert material, we can see a value of zero for sand and stones. The original benefit was -25.4% for the total treatment scenario, which means that recycling sand and stones in a complex mechanical separation plant requires more resources than the virgin production. Virgin production of sand and stones has a CEENE of 0.396 MJ per kg, compared to a CEENE of 1.29 MJ for the recycling process. We could thus say that the recycling of sand and stones is not advisable. On the other hand, it can be stated that the separation of sand and stones is no primary goal and giving this by-product a useful destination is beneficial. The use of iron oxide (rust) particles in cement gives a benefit rate of 17% and an absolute benefit of 0.24 MJ per kg of iron oxide. The absolute benefit is low compared to the other material categories because of the low CEENE of the virgin product. It was assumed that the iron oxide fraction consists entirely of rust particles, where in practise, also sand and other impurities might occur. Although this would not be a problem for the use in cement, it would lower the benefit.

Using the fibre-rich fraction as a substitute for polyelectrolytes in wastewater treatment plants has a benefit of 34.1% (20.7 MJ/kg). This scenario is hypothetical, as all fibres are incinerated nowadays. Other applications, such as the production of plate material, are under development and might have a higher benefit than the use as a sludge stabiliser. Further conclusions about the benefit of this material category will be made when compared to the energy recovery scenario.

4.3.2 Energy Recoverability Benefit Rate (ER_{cov})

The Energy Recoverability Benefit Rate expresses the benefit obtained by incinerating a certain product instead of landfilling it. Since the original formula by Ardente (2014) only takes into account the electricity and heat production, a modified formula had to be used in order to be suited for non-combustible materials. The Energy Recoverability Benefit Rate was calculated for two scenarios: a scenario with and without the recovery of metals from the bottom ash fraction. It is clear that the metal recovery scenario does not apply to the inert fraction and the fibre-rich fraction. Results are shown in Table 6.

The Energy Recoverability Benefit Rates show the same trends as the Recyclability Benefit Rates. Lead has a lower benefit than nickel, aluminium and copper in both scenarios. Precious metals suffer from a low recovery and have a lower benefit rate than metals. But again, the absolute benefit is higher for precious metals than for metals in case of incineration with metal recovery. On average, precious metal recovery from bottom ashes has an absolute benefit 252 times higher than the recovery of metals. Without the recovery of metals, there is almost no difference between the absolute benefit in both categories since the avoided virgin product is similar. Since the virgin production of precious metals requires much more resources (10^3-10^5 MJ/kg compared to 10^1-10^2 MJ/kg for metals), the benefit rate of using precious metals in bottom ashes as construction material is relatively low compared to the metals category. This benefit rate is below 1% for all material categories except for copper and the fibre-rich fraction.

Table 6: Overview of the Energy Recoverability Benefit Rates

	Incineration - Metal Recovery RVR = $\eta_{incineration} \cdot \eta_{ash\text{-}treatment} \cdot \eta_{end\text{-}processing}$		**Incineration - No Metal Recovery** RVR = $\eta_{incineration} \cdot \eta_{end\text{-}processing}$	
	Absolute Benefit [MJex/kg]	Relative Benefit Rate	Absolute Benefit [MJex/kg]	Relative Benefit Rate
Metals				
Nickel	9.29	3.51%	0.78	0.30%
Lead	0.68	2.01%	0.05	0.15%
Aluminium	25.01	11.45%	1.10	0.51%
Copper	15.26	13.99%	1.65	1.51%
Precious metals				
Silver	87.81	5.45%	0.07	0.0044%
Gold	6662.04	1.64%	1.14	0.0003%
Palladium	2759.71	1.31%	1.11	0.0005%
Inert fraction				
Sand and stones	/	/	0	0%
Iron oxide	/	/	0	0%
Fibre-rich fraction				
Car fluff	/	/	16.11	26.6%

It can thus be concluded that installing an ash-treatment for metal recovery is beneficial and can avoid a lot of losses.

These conclusions are not valid for the inert and fibre-rich fraction, because no metals can be recovered. Inert materials ending up in an incineration plant are 100% transferred to the bottom ashes. The extra impact of incineration results in a negative benefit for both iron oxide and sand and stones. These negative benefits were given a zero value.

The fibre-rich fraction is the only material category really suitable for energy recovery, as it consists of organic material and can thus be incinerated. The average Heating Value of 20 MJ per kg is sufficient to result in an Energy Recoverability Benefit Rate of 26.6%. This is rather low compared to the benefit rate of almost 47% in Debaveye et al. (2014). This difference can be attributed to a higher heating value used for plastics (42 MJ/kg). The benefit of incinerating the fibre-rich fraction can entirely be attributed to the generation of electricity. The use of bottom ashes as construction material has only 0.1% contribution to the environmental benefit rate.

4.4 Ratio of Recyclability Benefit Rate and Energy Recoverability Benefit Rate

The goal of this study is to compare the benefit of recycling certain material categories with sending them to an energy recovery facility, by calculating the ratio of the recyclability benefit rate and the energy recoverability benefit rate. A ratio higher than one means that recycling is preferred. The results are shown in Figure 12. Because of large differences in the ratio, a logarithmic scale was used for the Y-axis. Numerical values are given in Table 7. The ratio was calculated for the Total Treatment scenario. Results for the Final Treatment scenario are given in the appendix. The blue bar represents the ratio of recycling metals compared to incineration with ash treatment, the red bar is the ratio of recycling metals compared to incineration without ash treatment. The higher the ratio, the better recycling is compared to energy recovery.

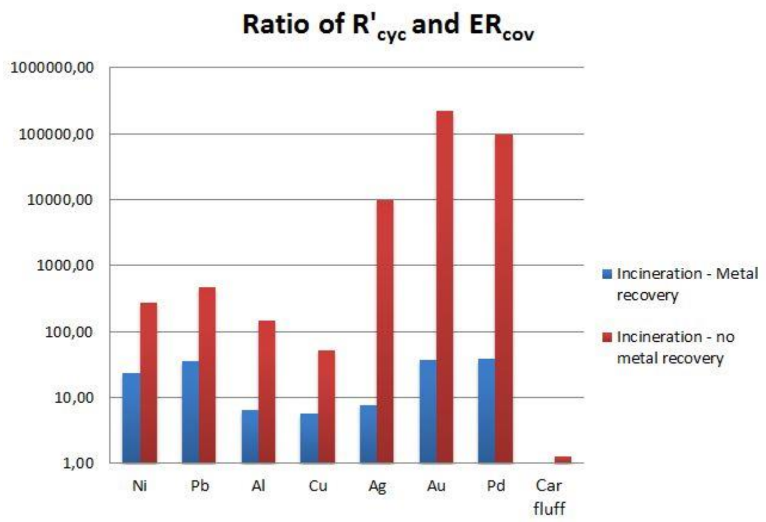

Figure 12: Ratio of the Recyclability Benefit Rate and Energy Recoverability Benefit Rate

The results are very consistent: all values are above one and thus, recycling is always the preferred scenario. The ratio is lower when recycling is compared with incineration with metal recovery than the comparison with incineration without metal recovery.

The high resource potential of metals and precious metals and the importance of the mechanical separation in the Post-Shredder techniques are highlighted by these results. Even if the ashes are treated, the benefit of recycling is 18 times higher for metals and 28 times higher for precious metals. This is a large difference between recycling and energy recovery that cannot be ignored. It can also be seen that the ratio is higher for precious metals, especially in the case without metal recovery. Precious metals are usually present in ores with very low concentrations and a lot of extensive processes are needed to produce the pure metal. If these precious metals end up in construction material, a big potential is lost. The production of the other metals also requires a lot of energy and resources, but this is less pronounced.

No conclusions can be made on the inert fraction since it was given a zero value. Using the fibre-rich fraction as a sludge stabiliser is slightly better than the energy recovery, but the value of 1.3 shows that the difference in benefits is relatively small compared to metals.

Table 7: Ratio of the Recyclability Benefit Rate and the Energy Recoverability Benefit Rate for different scenarios

	$\frac{Recycling}{Incineration\ (Metal\ Recovery)}$	$\frac{Recycling}{Incineration\ (No\ metal\ Recovery)}$
Metals		
Nickel	23.3	277.2
Lead	36.2	476.4
Aluminium	6.6	149.2
Copper	5.7	52.3
Average	18.0	238.8
Precious metals		
Silver	7.7	9683.8
Gold	38.1	222404.2
Palladium	38.5	95786.4
Average	28.1	109291.5
Inert fraction		
Sand and stones	/	0
Iron oxide	/	0
Fibre-rich fraction		
Car fluff	/	1.3

4.5 Sensitivity Analysis

In order to highlight the importance of some raw materials, an extra criticality weighting was performed. The criticality takes into account the supply risk and economic importance of different raw materials, as this can influence the European economy (European Commission, 2014). Criticality values could be obtained for nickel, aluminium, copper, silver, gold, palladium and iron oxide. The application of the criticality in the benefit rates was explained in section 3.6. Table 8 summarises the results of the criticality weighting. Only the benefit rates are shown, as the absolute benefit loses part of its meaning due to the weighting.

In the case of the recyclability benefit rate, criticality weighting results in a higher benefit rate, except for gold which has a lower criticality factor. The increase is larger for the metals than for the precious metals category, but in general the benefit rises with only a few percentage points. The benefit of iron oxide on the contrary almost quadruples and rises to 71.6%. On average, the benefit of metals and precious metals is almost equal.

The same trends can be seen in the energy recoverability benefit rate. In the incineratin scenario with metal recovery, the benefit rate of metals and precious metals increases slightly. In the case without metal recovery, the benefit rate decreases. This is because the criticality factor C only has an influence in the denominator of the formula. Since C is bigger than 1 for all materials except for gold, a decrease is easily explained.

Table 8: Overview of the criticality weighted benefit rates

	Recyclability Benefit Rate	Energy Recoverability Benefit Rate	
	Total Treatment	Incineration - Metal Recovery	Incineration - No metal recovery
Metals			
Nickel	84.99%	3.65%	0.14%
Aluminium	83.82%	12.79%	0.16%
Copper	79.7%	14.75%	1.20%
Precious metals			
Silver	45.13%	5.84%	0.0013%
Gold	61.41%	1.61%	0.0005%
Palladium	51.20%	1.33%	0.0001%
Inert fraction			
Iron oxide	71.61%	/	0%

As such, the criticality weighting does not have a big influence on the benefit rates. The importance of metals recycling is already shown in the high environmental impact of the virgin production, being at least a factor 10-100 higher than the CEENE value of the recycling processes. Since C is used in both the numerator and denominator, the influence of the weighting is limited. Therefore, it can be concluded that the results are relatively robust, regardless of an extra weighting.

5 Conclusion

The goal of this project was to get a more complete idea of the impacts and beneftis of the valorisation of shredder residues by analysing the resource benefit of specific materials in four material categories: metals, precious metals, an inert fraction and a fibre-rich fraction. For every material category, recycling was compared to energy recovery. The benefit represents the avoided virgin production and landfill disposal of a certain product, taking into account the cost of the different recycling processes. Formulas introduced by Ardente (2012) were used and slightly modified for this analysis. In general, the formulas were useful, but adjustments were required to account for the avoided landfill and virgin materials replaced by valorising the bottom ash fraction. In this new formula, the ash treatment processes were included, a treatment that is often ignored in end-of-life treatment processes.

First, the Material Flow Analysis was obtained. The different treatment processes were studied and the recovery of materials in these processes was analysed. Figure 13 shows the three scenarios Total Treatment, Incineration - Metal Rrecovery and Incineration – No Metal Recovery. The Final Treatment scenario, which does not take into account losses in the shredders and PST is shown in appendix. The same trends can be seen for the materials: in the Total Treatment scenario, most of the metals are recycled into secondary metal. Both incineration scenarios however have construction material as the most important end-products.

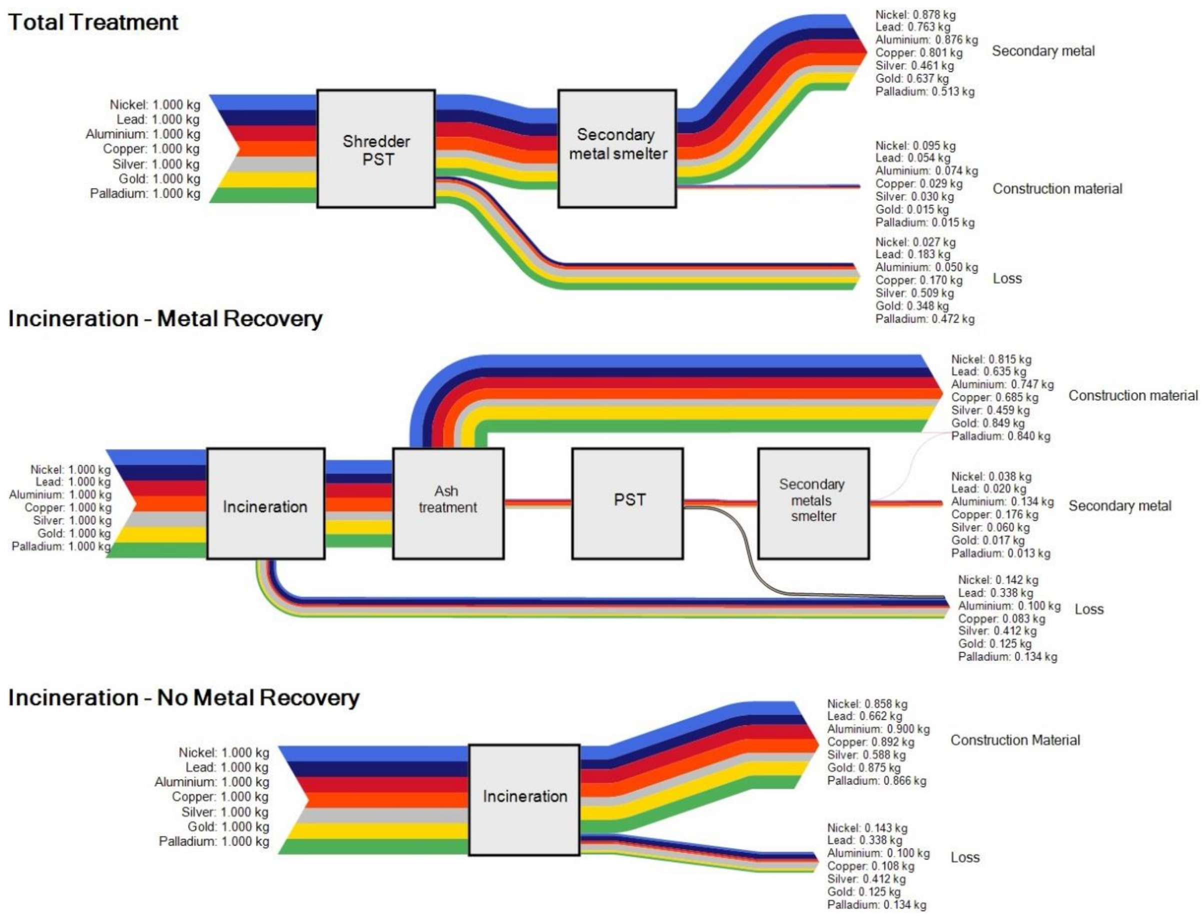

Figure 13: Overview of the material flows for metals and precious metals

Next, the environmental impact of these processes was modelled for the total resource consumption throughout the whole lifecycle. This resource consumption was calculated with the CEENE method (expressed in MJ exergy) and used in the benefit rates to calculate the ratio of the recycling scenario and the energy recovery scenario.

An overview of the results is given in Figure 14. The Recyclability Benefit Rate is larger than the Energy Recoverability Benefit Rate, with big differences for all materials. These differences are bigger between the different material categories compared to differences within the material categories. Therefore, material categories are useful and an average value for these categories could be used. On average, 77.3% of the total resource consumption of metals can be recovered by recycling, compared to 51.6% for precious metals, 17.0% for the inert fraction and 34.1% for the fibre-rich fraction. This means that more than half of the original resources for metals and precious metals can be recovered by recycling. The benefit rate of the inert fraction and fibre-rich fraction is lower, but as they are a by-product of the mechanical separation process, every avoided landfill can be seen as a benefit.

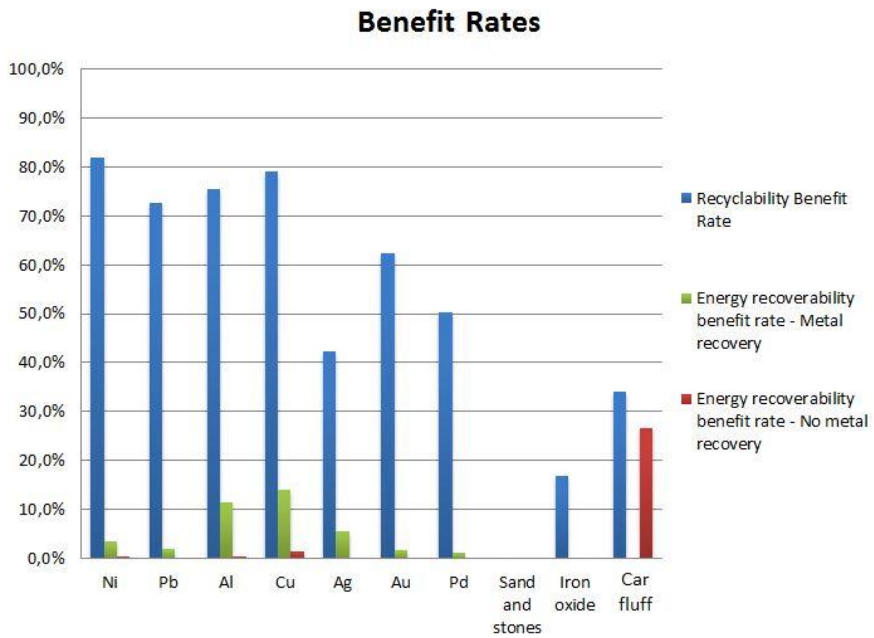

Figure 14: Comparison of the Recyclability Benefit Rate and Energy Recoverability Benefit Rate

Both energy recovery scenarios give a lower benefit due to losses that occur in the incineration and ash-treatment plants. The energy recoverability benefit rate for metals has an average of 7.74% in case of metal recovery, which is higher than 2.81% for precious metals. This is due to an average recovery of aluminium and copper, which have a larger size than precious metals that are used as very thin coatings.

The energy recoverability benefit rate without metal recovery is so low that it is almost invisible on the chart. The average values of 0.62% for metals, 0.0017% for precious metals and 0% for inert materials are due to the low resource consumption of the production of construction material compared to the very high consumption of virgin products. The fibre-rich fraction is an organic material and energy can be produced by its incineration. Subsequently, the benefit rate of this incineration is 26.6%.

It is clear that in all cases, recycling is the preferred scenario, but improvements are possible by a good ash treatment. In order to make a clear comparison, the ratio of the recyclability benefit rate and energy recoverability benefit rate was made. The averages per material category are summarised in Table 9.

Table 9: Summary of the ratio of the Recyclability Benefit Rate and Energy Recoverability Benefit Rate per material category

	$\frac{Recycling}{Incineration\ (Metal\ Recovery)}$	$\frac{Recycling}{Incineration\ (No\ metal\ Recovery)}$
Metals	18.0	238.8
Precious metals	28.1	109291.5
Inert fraction	/	0
Fibre-rich fraction	/	1.3

This table highlights the conclusion that recycling has a higher benefit compared to energy recovery and should be encouraged in environmental policies. Due to losses during the treatment of bottom ashes, an extensive treatment in a mechanical separation plant is the best way to recover as much of the initial value as possible. The difference between the scenarios with and without metal recovery shows that construction material does not generate a very high benefit. It is a decent way to process by-products, but causes a big loss in resource potential for metals and precious metals. Therefore, the recovery of metals from bottom ashes is promising and an enhanced recovery could result in large environmental gains.

More information is needed about the behaviour of metals during incineration in order to improve the subsequent ash-treatment processes for maximal recovery of metals and precious metals. As more than half of the precious metals are lost both in the mechanical treatment plant as in the ash-treatment facility, an enhanced recovery will result in enormous resource savings. Next, new destinations should be found for the fibre-rich fraction, as this research shows that the benefit of incineration can be easily surpassed.

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Appendix

A. Individual process efficiencies

Table 10 gives an overview of the individual process efficiencies used to calculate the Recycling Rate. These efficiencies are the same used to calculate the Recovery Rate, as these treatments are the same for both scenarios.

Table 10: Individual process efficiencies contributing to the Recycling Rate (RCR)

Material	Destination	$\eta_{shredder}$	$\eta_{end\text{-}processing}$
Metals			
Nickel	Secondary nickel	97.3%	90.2%
	Construction material		9.8%
	Loss	2.7%	
Lead	Secondary lead	81.7%	93.3%
	Construction material		6.7%
	Loss	18.3%	
Aluminium	Secondary aluminium	85.5%	97%
	Secondary aluminium (China)	4.75%	
	Construction material (Aluminium smelter)		3%
	Construction material (Umicore)	4.75%	
	Loss	5.0%	
Copper	Secondary copper (Copper smelter)	35.35%	96.6%
	Secondary copper (Integrated smelter)	46.18%	96.6%
	Secondary copper (China)	4.69%	55%
	Construction material		3.4%
	loss	13.8%	
Precious metals			
Silver	Secondary silver	49.1%	94%
	Construction material		6%
	Loss	50.9%	
Gold	Secondary gold	65.2%	98%
	Construction material		2%
	Loss	34.8%	
Palladium	Secondary palladium	52.8%	97%
	Construction material		3%
	Loss	47.2%	
Inert material			
Sand and stones	Construction material	48.0%	100%
	Loss	52.0%	
Iron oxide	Cement production	100%	100%
Fibre-rich fraction			
Car fluff	Wastewater treatment	100%	100%

The next table displays the process efficiencies of the incineration and ash treatment. The incineration efficiency shows the amount of material that is transferred to the bottom ash fraction. The ash-treatment efficiency consists of the efficiency of the ash-separation and the efficiency of the PST. As the latter is the same as $\eta_{shredder}$, the values are not repeated but can be found in Table 10. The same is valid for $\eta_{end\text{-}processing}$.

Table 11: Individual process efficiencies contributing to the Recovery Rate (RVR).

Material	$\eta_{incineration}$	$\eta_{ash\text{-}separation}$
Metals		
Nickel	66.2%	5%
Lead	85.8%	4%
Aluminium	90.0%	17%
Copper	89.2%	25%
Precious metals		
Silver	58.8%	22%
Gold	87.5%	3%
Palladium	86.6%	3%
Inert material		
Sand and stones	100%	/
Iron oxide	100%	/
Fibre-rich fraction		
Car fluff	30%	/

B. Benefit rate

Table 12: Recyclability benefit rate for the Final Treatment scenario

	Final Treatment RCR = $\eta_{end\text{-}processing}$	
	Absolute Benefit [MJex/kg]	Relative Benefit Rate
Metals		
Nickel	222.5	84.2%
Lead	30.3	89.0%
Aluminium	182.5	83.6%
Copper	57.3	92.5%
Precious metals		
Silver	1385.0	86.0%
Gold	389342.5	95.7%
Palladium	200933.7	95.2%
Inert fraction		
Sand and stones	0	0%
Iron oxide	0.26	17.0%
Fibre-rich fraction		
Car fluff	20.7	34.1%

Table 13: Criticality weighted benefit rates for the Final Treatment scenario

	Recyclability Benefit Rate
	Final treatment
Metals	
Nickel	93.02%
Aluminium	92.87%
Copper	93.36%
Precious metals	
Silver	92.00%
Gold	94.22%
Palladium	96.89%
Inert fraction	
Iron oxide	71.61%

C. Ratio

Table 14: Ratio of Recyclability Benefit Rate and Energy Recoverability Benefit Rate for the Final Treatment scenario

	End-processing RCR = $\eta_{end\text{-}processing}$	
	$\frac{Recycling}{Metal\ Recovery}$	$\frac{Recycling}{No\ metal\ Recovery}$
Metals		
Nickel	23.75	284.92
Lead	33.64	583.16
Aluminium	7.28	168.21
Copper	6.61	61.09
Average	20.56	273.59
Precious metals		
Silver	15.69	19318.12
Gold	58.44	341207.14
Palladium	72.81	181266.96
Average	48.98	180597.41
Inert fraction		
Sand and stones	/	0
Iron oxide	/	0
Fibre-rich fraction		
Car fluff	/	1.28