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Executive summary

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Improvement of resource efficiency in the metal industry – substitution of primary raw materials through optimized alloy-specific recycling

by:

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Abstract: OptiMet

The “OptiMet” project, which has been funded by the German Federal Environment Agency, was concerned with increasing resource efficiency in the metals industry with regard to the substitution of primary raw materials. These are currently used in high concentrations in the recycling of metallic alloys in order to dilute undesirable accompanying elements (impurities). In the process, alloying elements are lost in a dissipative manner. This results in downcycling. It was the main goal of the OptiMet project to determine whether and to what extent higher selectivity can be achieved through innovative sorting techniques (camera/sensor systems) for select alloy types in order to a) reduce downcycling and thus enable functional recycling and b) to reduce the required input of primary raw materials.

The focus of the study was the alloy-specific recycling of steel, aluminum, copper, and zinc scrap. To evaluate the suitability of different sorting methods for these commercial mixed scrap materials, the currently available methods XRF, XRT, LIBS, NAA, and LIF were investigated and compared with respect to the detection of the element distribution and the concentration of impurities in various scrap fractions. The performance was evaluated according to the achieved selectivity. By comparing sorting and separation techniques, a suitable process chain, the associated resource conservation and primary raw material savings potentials, and the greenhouse gas emissions were determined. In addition, fundamental definitions for the terminology used were proposed; control variables for recycling and downcycling, rules for lean product design and political recommendations for action to better harness previously unused recycling potential were suggested.

1 Background

Over the past 150 years, the demand for metals has increased considerably for key sectors such as the energy, transportation, manufacturing, and communication industries. In addition to bulk metals such as iron, aluminum, and copper, alloying elements such as magnesium, silicon, and manganese are becoming increasingly indispensable because they perform important material functions for subsequent applications. Technical innovations in the fields of mobility, energy conversion and storage as well as building structures require new functional materials and alloying elements. In the meantime, almost the entire periodic table is represented.

However, the issue of recyclability has so far hardly played a role in the development of new materials. The trend towards the diversification of alloys, which is counterproductive for subsequent high-quality recycling, continues and thus leads directly to downcycling. At the same time, less than half of Europe’s metal requirements are covered by its own reserves. As a result, Europe is highly dependent on globally distributed deposits and thus on the respective political conditions. High-quality or functional recycling is therefore the only way to counteract both the dependence on and scarcity of metallic resources and to minimize the existing losses.

However, the recycling of alloys has its limits. This is because the additives are sometimes required – and, above all, the unneeded accompanying elements that enter the cycle as a result of global trade and the various manufacturing processes – are usually present in such low concentrations and in such a complexly distributed form that separation in the metallurgical process is extremely difficult and can rarely be achieved economically with the current processing methods. As a result of closed-loop recycling, these accompanying elements (e.g., copper in steel) successively accumulate in the melt. This unwanted loss of quality (i.e., downcycling) is currently being countered by adding high quantities of primary material as a diluent for interfering elements in the production of new alloys.

The aim of this project is to considerably reduce the proportion of primary raw materials required for dilution by intelligent (i.e., much more alloy-specific) sorting prior to the actual preparation process (e.g., pyrometallurgy) and to recycle the alloying elements via this route.

2 Project

The project, which was funded by the German Federal Environment Agency, was concerned with increasing resource efficiency in the metal industry with regard to the substitution of primary raw materials and the increase of functional recycling. The focus was on investigating the possibilities of the alloy-specific recycling of steel, aluminum, copper, and zinc scrap. The investigation of different scrap fractions before or after innovative sorting and separation processes was intended to provide new insights. In addition, control variables for recycling and downcycling as well as rules for low-sort design were determined. Based on the results of the analysis, recommendations were developed in order to better harness previously untapped high-value metal potential. The evaluation criteria include the potential savings in raw materials and greenhouse gas emissions as well as the cost structure for the production of alloys from recycled materials.

The successful provision of secondary raw materials (i.e., with minimal downcycling processes) required a comprehensive knowledge of the existing recycling structures, technological potentials, metallurgical process simulations and evaluation approaches developed and used in this project.

3 Procedure

The project was carried out by scientists from four research institutes. The coordination was the responsibility of the HZDR and here the Helmholtz Institute Freiberg for Resource Technology (HIF). The project was divided into five work packages (WP):

WP1 Downcycling – an overview (University of Augsburg)

In WP1, the definitional basis for the topic of downcycling of alloys was established. Until now, there was no standard definition for the term downcycling.

WP2 Downcycling – status quo and outlook (Wuppertal Institute for Climate, Environment and Energy/Technical University of Dortmund)

In WP2, data on the status quo of the occurrence and recycling routes of alloy groups at the German, European, and global level were collected for the present time as well as for the year 2030. Based on this, the expected dissipative losses and possible ecological and economic effects resulting from the avoidance of such losses were determined.

WP3 Innovative analysis and sorting techniques – implementation of sorting and separation processes (HZDR, Helmholtz Institute Freiberg for Resource Technology)

In order to assess the suitability of different sorting techniques for commercial mixed scrap, innovative analysis and sorting techniques were investigated using XRF, XRT, LIBS, NAA, and LIF and compared with respect to the detection of element distribution and concentration in various scrap fractions. Based on the experiments, the suitability, opportunities and risks of innovative sorting technologies are presented and application-oriented solutions are developed – also with the aid of metallurgical simulation tools. The innovative sorting techniques will then be combined with the separation techniques available on the market, and the percentage improvement in sorting and separation efficiency will be presented.

WP4 Evaluation (Wuppertal Institute for Climate, Environment and Energy)

The results of WP1 to WP3 are combined in WP4. Based on the comparison of sorting as well as upstream and downstream separation techniques, the associated resource conservation and primary raw material savings potentials are determined using the example of the ideal process chain.

WP5 Recommendations (Technical University of Dortmund)

Finally, options for action that enable the identified potentials to be transferred into practice are identified. Economic, political, and legal factors are taken into account. With the help of an impact analysis, the options and measures are evaluated, and final recommendations are derived.

Together with representatives from politics, associations, science, and industry, the interdisciplinary team examined the conclusions from various perspectives and compiled the results in this report.

4 Summary of the results

4.1 WP1 Downcycling – an overview

Definition of the term downcycling

The term “downcycling” is a combination of the words “down” and “cycling”. The term thus describes a downward direction of close-loop recycling but without specifying what exactly is meant by the downward direction. In the context of the circular economy, the term downcycling is a variation of the term “recycling”, which is defined, for example, in the German Recycling Law (KrWG).

Based on the uses of the term “downcycling” in the literature, the following working definition emerged in the “OptiMet” project: **Downcycling is the phenomenon of “reducing the quality of products, materials, or substances processed from waste compared with the original quality”.**

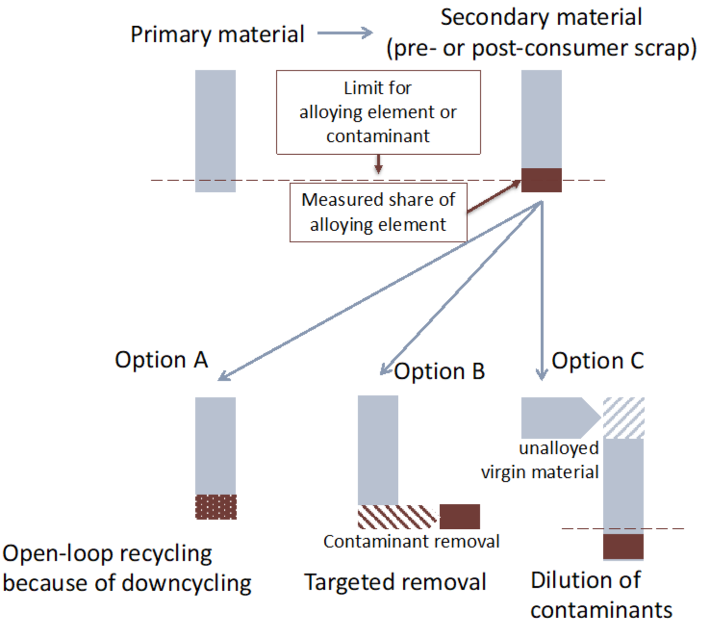
When it comes to reducing product quality, a distinction can be made between thermodynamic, functional, and economic downcycling:

- **Thermodynamic downcycling** occurs when more thermodynamic effort in the form of energy, heat, labor, or aggregates is required to prepare a product, material or substance from waste from secondary materials than is required to produce the same product, material or substance through pure remelting.
- **Functional downcycling** occurs when the possible range of uses of a product, material or substance reprocessed from waste covers fewer purposes than the range of uses of the same product, material or substance produced through pure remelting.
- **Economic downcycling** occurs when the specific use value (usually commercial price) of a product, material or substance processed from waste is lower than the value of the same product, material or substance produced through pure remelting.

Downcycling is also related to the equally problematic phenomenon of dissipation; however, the terms are not synonymous. While alloys of the main metal lose quality through downcycling, dissipation describes the loss of alloying elements (e.g., as a result of the recycling process).

The reasons for downcycling are also different. Downcycling can be caused by dilution, contamination by impurities (Figure 1), the oversupply of secondary material, or product design.

Figure 1: Schematic representation of the possible courses of action in downcycling



Schematic graphic, source: own graphic, University of Augsburg

Downcycling is particularly problematic if the reduction in the quality of the secondary materials means that increased environmental impacts are to be expected. This is the case if: a) a high quantity of primary raw materials is required in order to ensure the required material qualities at least to some extent using secondary raw materials b) a high demand for energy or exergy is required to process the secondary raw materials c) functional metals (alloying components) such as copper, tin, or cobalt are "removed" as impurities in a costly manner (i.e., by dilution and not by recovery). This causes the irretrievable loss of alloying elements (e.g., via the slag or fine dust).

Quantification of downcycling

There is no universally accepted measure of the "quality" of a material to which a definition of downcycling can refer. Instead, quality specifications always depend on the function and the area of application. Irrespective of this, we agreed on a baseline (zero line) for the calculations in the "OptiMet" project. This describes the primary raw material requirement in the pyrometallurgical process if exactly the same quality or original alloy is to be produced again from an input alloy (pure remelting). Accordingly, the comparison should always take place at the process stage in the material cycle in which primary raw materials are in direct competition with the use of secondary raw materials. The thermodynamic or exergetic evaluation therefore emerged as the most suitable for quantifying the downcycling effect.

Recycling compatibility matrix

Whether an impurity contained in the waste stream is classified as an impurity or a desired alloying metal depends on the behavior of the element in the recycling process as well as on the material produced. In the recycling process, the decisive factor is whether the element remains in the metal phase or (because of its reactivity) is co-deposited in the solid slag phase or the gas phase and thus separated from the main metal. If it remains in the metal phase, a separation in the recycling process is difficult. This, in turn, limits the scope of application of the secondary material if the material properties are deteriorated.

Table 1: Compatibility of alloying elements with materials of alloying categories.

Element	Steel	Al alloy	Cu alloy	Zn alloy
Fe	Base	✗	-	-
Al	✓	Base	✓	✓
Cu	✗!	✗	Base	✓
Zn	✓	(✓)	✓	Base
Mg	-	✓	-	✓
Si	-	✗	-	-
Ti	-	✗	-	-
Cr	✓	✗	-	-
Mn	✓	✗	-	-
Ni	✗	-	✓	-
Mo	✗	-	-	-
Nb	✓	-	-	-
V	✓	-	-	-
W	✗	-	-	-
Co	✗	-	-	-
Sn	-	-	✓	-
Pb	-	-	✗!	-
Bi	-	-	✗!	-

✓: Element that can be separated in the usual recycling process. (✓): Element that can be only partially separated. ✗: Element that cannot be separated. -: No alloying element of this alloy class. !: Impurity of this alloy class. Base: Base metal of the alloy class.

The literature has examined the extent to which waste streams should be separated for various metallurgical processing operations. For aluminum recycling, all other metals must be separated, while copper and zinc in recycled copper, lead, and zinc alloys can be incorporated quite well. Zinc alloys can be processed in the copper, steel, and zinc routes.

In summary, compatibilities for recycling with respect to impurities can be indicated (Table 1).

For steel, copper in particular should be mentioned as an impurity. In the case of aluminum, only magnesium and some zinc can be separated as scrap in the recycling process. In copper recycling, special attention is paid to lead contamination from lead-containing brass alloys and to avoiding the input of bismuth into conductive copper. The common alloying elements for zinc can be easily separated in the recycling process.

Example of aluminum

In this summary, only selected results and specifically aluminum will be discussed in the following chapters.

In general, a distinction is made between wrought and rolled aluminum alloys (usually abbreviated to wrought alloys) and casting alloys.

Typical wrought alloys are: 1100 for food packaging (aluminum foil), 1350 for electrical conductors, 3003 for heat exchangers, 3004 for beverage cans (whereby the opening clip is usually made of 5182), 5052 for gas containers, 6063 for vehicle frames, and 7050 and 7075 for aerospace applications (Hatayama et al. 2006). The average composition of selected wrought alloys is given in Table 2 .

Table 2: Average weight percentages of alloying elements for selected aluminum alloys (The Aluminium Association 2015). Aluminum makes up the missing mass fraction to account for 100%.

No.	Comment	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
1235	Household aluminum foil	0.65 (Si + Fe)[1]		0.05	0.05	0.05	-	0.1	0.06
3003	Most common 3xxx alloy	0.6	0.7	0.13	1.25	-	-	0.1	-
5182	Aluminum can closure	0.2	0.35	0.15	0.38	4.5	0.1	0.25	0.1
6063	Most common 6xxx alloy	0.6	0.35	0.1	0.1	0.68	0.1	0.25	0.1
1350	Conductive aluminum	0.1	0.4	0.05	0.01	-	0.01	0.05	-
3004	Aluminum cans	0.3	0.7	0.25	1.25	1.05		0.25	-
5083	Shipbuilding (plates)	0.4	0.4	0.1	0.7	4.45	0.15	0.25	0.15
6061	Second most common 6xxx alloy	0.6	0.7	0.28	0.15	1.0	0.21	0.25	0.15
8011	Alternative aluminum foil	0.7	0.8	0.1	0.2	0.05	0.05	0.1	0.08

The most common alloying elements for aluminum are magnesium, silicon, titanium, chromium, manganese, iron, copper, and zinc. Other alloying metals can be nickel, silver, boron, bismuth, gallium, lithium, lead, tin, vanadium, and zirconium (The Aluminium Association 2015). In addition, a maximum of 0.05% is usually allowed per element not explicitly listed. In total, such elements may not account for more than 0.15% by weight. There are no known impurities that may not be contained in aluminum alloys at all.

The most important application for cast aluminum alloys, which contain higher levels of alloying elements overall, are engine blocks in vehicle construction (Nakajima et al. 2010). Downcycling could become an even bigger problem for aluminum if the demand for casting alloys for engine blocks of combustion engines decreases. This is because these currently represent a major sink for alloying metals.

Currently, about one-third of global demand for aluminum alloys consists of 6xxx alloys. Alloy groups 1xxx, 3xxx, 5xxx, and 8xxx are also important. About one quarter of demand is for casting alloys.

Scrap from aluminum alloys is primarily used for the production of casting alloys, whereas primary aluminum is mainly used for wrought alloys. Aluminum scrap is typically processed

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[1] The combined mass fraction of silicon and iron is 0.65%.

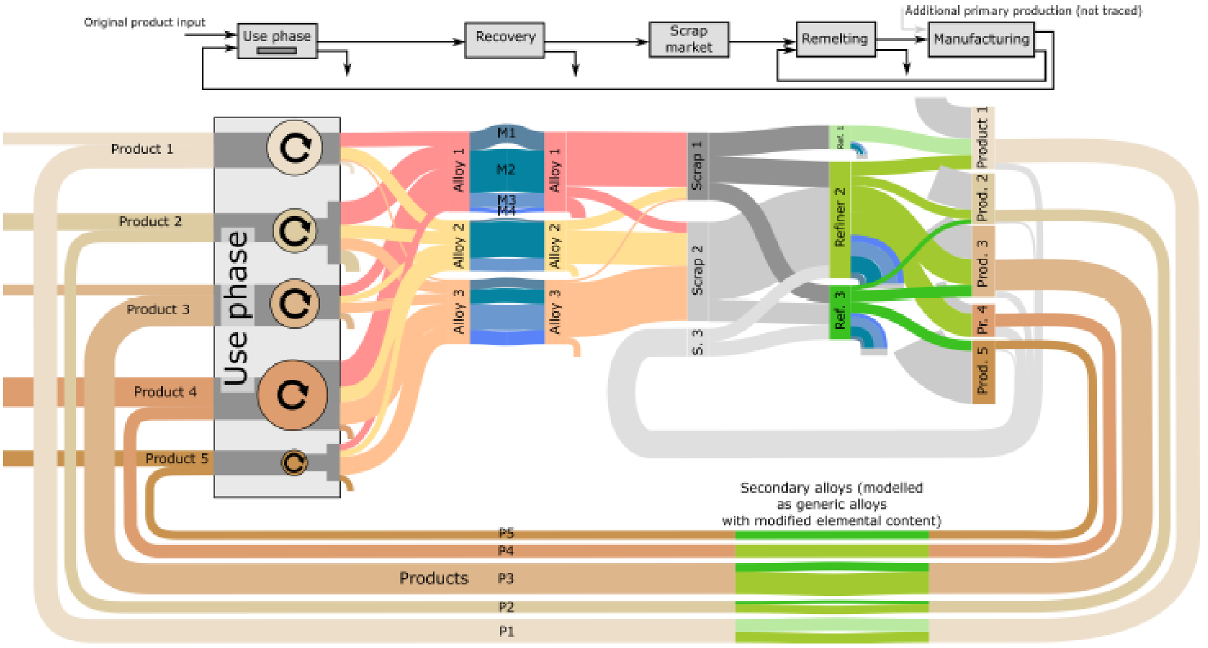
either in the remelting process or the refining process (Cullen and Allwood 2013). Remelters (<10% alloying elements) produce rolled and extruded products in this process. Strict requirements apply to the secondary materials used. This is why mainly new scrap or production waste with a well-defined composition and only a small amount of old scrap is used. Refiners (< 20% alloying elements) have lower quality requirements and therefore receive the most scrap.

For the automotive sector in particular, it is being investigated to what extent higher recycling rates would be possible by improving the separation of scrap. This is because the wrought alloys are mainly recycled as casting alloys and thus not in a function-preserving manner.

4.2 WP2 Status quo and forecast

This work package is about determining the volume and recycling routes of steel, aluminum, copper and zinc alloys as status quo and forecast until 2030. Data are considered at the German, European and global levels. First, general quantity structures are determined. This allows the calculation of the expected dissipative losses through downcycling as well as possible ecological and economic effects through the avoidance of these.

Figure 2: A definition for alloy-specific material streams in a system



Source: Nakamura et al. 2017

Because data on scrap occurrence is available in different qualities and often not at all, one objective of the project was to create a comparable database for some selected alloy types. To this end, the approach is consistent across the three geographic levels (German, EU, global). The starting point is the scrap volumes of waste streams (Figure 2) that go to recycling plants as input (e.g., end-of-life vehicles or construction and demolition materials).

Researched metal contents, such as those contained in the UBA report “ReSek” (2018), then suggest the metal contents of steel, aluminum, copper, and zinc. While new scrap or production waste is usually well-defined and thus quite easy to recycle, mixed scrap (e.g., electronic scrap) is quite complex in composition; almost all elements of the periodic table are present as alloying constituents. This makes the recycling and recovery of valuable metals quite difficult. For example, less than 1% of germanium is recovered from such material streams.

In terms of volume, mixed scrap accounts for about 30–40% of the total volume.

A five-step approach is used to quantify the main metals:

1. Determination of the supply, demand and scrap volume of the main metals of the status quo
2. Definition of the relative proportions (conversion factors) of the main alloys in total metal consumption
3. Calculation of the quantities of main alloys
4. Derivation of the forecast for the year 2030 based on existing scenarios
5. Verification of the results via expert interviews and corresponding adjustments

Example of aluminum

Raw metal is defined as refined aluminum, which is traded in the form of ingots and bars. It thus includes both primary and secondary aluminum. The supply of aluminum for the year 2016 was 3,954 kt in Germany, 13,586 kt in Europe and 88,726 kt worldwide. The demand is calculated taking into account exports of the raw metal and foreign trade of the semi-finished product as well as new scrap of the semi-finished product production. The latter include new scrap, dross, slag and losses as a result of dusts. Only streams leaving the smelting works were considered. There are also new scraps that are remelted within the works. The report shows the proportion of new scrap that can be directly remelted because of its high-grade purity. Such scrap is produced at downstream works that process semi-finished products. In some cases, it is transported directly back to upstream smelting works, where it is used. As an exception, inventory changes for Germany were taken into account. These were used primarily to align with published WVMetals data. For 2016, this results in demand of 3,350 kt for Germany, 11,544 kt for Europe, and 77,901 kt worldwide.

As expected, the results show Germany’s dependence on imports of aluminum. For example, Germany imports about twice as much unwrought aluminum as is produced domestically. In addition, Germany has a pronounced foreign trade in semi-finished products with a slight export surplus. Import dependency is also evident at the European level. About half of the unprocessed aluminum is imported. European foreign trade in semi-finished products shows a slight import surplus and is lower than German foreign trade. This is because a large part of German foreign trade relates to the European market. In turn, European foreign trade takes only non-European trade into account.

The scrap volume also consists of both wrought and casting alloys. A distribution by alloy group is useful only for the wrought alloy scrap. As with the differentiation of demand, a 70–30% ratio is assumed between scrap from wrought alloys and casting alloys.

In accordance with the calculations made in this report, German demand for aluminum will increase from 3,350 kt in 2016 to 3,830–4,170 kt in 2030. This corresponds to a 14.3–24.5% increase in demand. A similar development can be observed at the European level: Here, aluminum demand will increase from 11,544 kt (2016) to 13,560–15,355 kt in 2030. This corresponds to an increase of 17.5–33% over the 14-year period considered. The increase in demand is slightly stronger at the European level than at the German level. At the global level, an increase from 77,901 kt (2016) to 101,178–122,826 kt is expected in 2030. The result corresponds to a 29.9–57.7% increase over the 14-year period. According to the report, global aluminum demand is growing much faster than at the German and European level. At the global level, in accordance with the IAI, aluminum demand is expected to reach 120,000 kt in 2030. This is within the interval of global aluminum demand calculated here.

The study of the OECD suggests a global aluminum demand of 210,000 kt for 2060. Taking into account the calculated results, a 71–108% increase in global aluminum demand over a 30-year period would follow. This corresponds to annual growth of 1.8–2.5%.

In this context, an essential aspect is the consideration of the available aluminum scrap that flows into secondary production. At the global level, for example, about 26,000 kt of aluminum scrap went back into aluminum production in 2014. At the European level, the figure was around 3,700 kt. However, it is unclear how much aluminum scrap was available beyond this and thus remained unused. It can be derived that globally 33,778 kt of aluminum scrap will be returned to production in 2030. In addition, 10,877 kt will not be recycled. A global scrap volume of 44,655 kt of aluminum can thus be assumed in 2030. In 2016, the scrap volume was 23,707 kt. This corresponds to a growth of around 88%. No forecast is available here for the European level.

The future development of aluminum demand and scrap volumes depend on many factors. This also includes the technological development of individual sectors because these are closely linked to material requirements.

The application areas with high relevance for aluminum continue to be the automotive and aerospace industries as well as shipbuilding. Reasons for this are lightness coupled with damage tolerance, corrosion resistance, stiffness, and strength. Aluminum alloys containing scandium are of particular importance here.

The addition of scandium allows welding instead of riveting the material. Novel aluminum-lithium alloys are also becoming increasingly important for aircraft frame construction. The lower density and improved material properties lead to the desired weight reductions. Another considerable factor in the transportation sector with regard to alloy-specific aluminum demand is the establishment of electromobility in the passenger car sector. Casting alloys are currently being used for combustion engines in passenger cars. If electromobility becomes established, the demand for internal combustion engines – and thus the need for casting alloys – will decrease.

Quantification of downcycling

For the base metal aluminum, only wrought alloys are listed here. The basis is the publication “International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys” (International Aluminum Association, 2015) and the ‘Teal Sheet’. This document contains a list of 528 different wrought alloys and their chemical composition or the limits for certain chemical elements that must not be exceeded. These data are not available for casting alloys and the composition of these.

The following elements are shown as a percent concentration: Si, Fe, Cu, Mn, Mg, Cr, Ni, Zn, Ti, Ag, B, Bi, Ga, Li, Pb, Sn, V, and Zr. For Si, Fe, Cu, Mn, Mg, Cr, Zn, and Ti, ranges or limits are given for almost all 528 alloys. Other chemical elements, such as Pb, Ni or Ga, are used only in a few alloys and are accordingly named as limits or ranges in only a few alloys in the Teal Sheet.

Certain alloying elements are found only in certain specific alloys but are sometimes present in high concentrations. For example, in the 38 alloys of the 8xxx group, lithium is contained in five wrought alloys. In four of them, the concentration is quite high and ranges from 2.25 to 3.8%.

In order to be able to estimate the downcycling effects, in addition to estimating the chemical composition of the scrap quantities, it is necessary to define typical target alloys, the production of which was depicted using the HSC simulation software of the HZDR (HIF). After a literature search and internal discussions, two alloys were selected for each of the most important alloy groups (6xxx, 1xxx, 3xxx and 5xxx) for wrought aluminum alloys. It was assumed that one of the two alloys would be produced from 50% of the scrap quantity for each alloy group. One alloy each was selected from the remaining alloy groups (2xxx, 4xxx, 7xxx, and 8xxx). The simulated calculation thus shows the necessary amount of alloying metals and raw aluminum that must be added in addition to the scrap in order to produce alloy 8011 from a scrap mixture of the 8xxx group, for example.

This is the post-dilution effect and thus a part of downcycling. Other aspects of downcycling include the losses of alloying metals that are contained in the scrap but which are not part of the target alloy. These non-essential metals may be impurities that require post-dilution or which may be lost as bound stray metals in the new wrought alloys. Another aspect is metal losses resulting from the transfer of these metals into the slag or dusts during manufacturing.

The strongest post-dilution effects are shown in the simulation calculations for the production of the target alloys of the 2xxx group (2007) and the 7xxx group (7020). In contrast, the weakest post-dilution effects are shown for the target alloy 1350, the two 3xxx alloys, and the two 5xxx alloys.

As a result of the simulation calculations for Germany, the total dilution effects in the production of the various target alloys amount to 179.7–239.5 kt (depending on the degree of mixing). In each case, this is almost completely determined by primary or raw aluminum (174.1–232.2 kt). In terms of alloying elements, the main ones to be added are magnesium (1.74–2.32 kt), crude iron (1.20–1.60 kt), silicon (0.59–0.79 kt), manganese (0.57–0.76 kt) and zinc (0.48–0.64 kt). Copper (0.39–0.52 kt), chromium (0.24–0.32 kt) and titanium (0.21–0.28 kt) are other relevant alloying metals that must be added because of dilution effects. This means that 353.0–470.7 kt of wrought aluminum alloys would be produced by post-dilution with a mixed scrap input of 173.4–231.2 kt under the assumptions used here. This would correspond to 15–20.0% of the volume of wrought aluminum alloys actually demanded in Germany.

Another result is that the distribution of demand by alloy group will change little by 2030; accordingly, the scrap composition and thus the quantities of target alloys will also change little. Thus, the amounts of primary aluminum and alloying metals that need to be added because of post-dilution will grow in parallel with the scrap amount and thus correspond to 217.7–236.2 kt for a presumed 30% blend of the scrap volume or 290.3–314.9 kt for a 40% blend. The percentage composition between primary aluminum and alloying metals remains unchanged. Thus, it is estimated that even in 2030, 97% of the post-dilution will be primary aluminum.

In addition to dilution effects, there are also losses of alloying metals that, although contained in the scrap, are not needed in the target alloy and either remain bound in the base metal (even as an interfering element) or are partially lost in slags and dusts. In 2016, this quantity for Germany amounts to 0.38–0.51 kt of alloying elements, of which the most important are bismuth (0.11–0.14 kt), tin (0.08–0.10 kt), lead (0.05–0.06 kt), and magnesium (0.05–0.07 kt). In 2030, losses will increase in parallel with the amount of scrap to 0.39–0.42 kt (30% blend) and 0.52–0.56 kt (40% blend), respectively. The composition of these losses by individual alloying metals is similar to that in 2016.

Environmental impact

Using 173.4 or 231.2 kt of aluminum scrap in Germany in 2016 (from which 353.0–470.7 kt of new wrought alloys are produced) results in a cumulative raw material input of 2,872–3,829 kt. Because most of the dilution effects involve primary aluminum, the proportion of primary aluminum contributing to the environmental effects is also correspondingly high (2,416–3,221 kt or 84%). The high energy requirements of aluminum production – and thus greenhouse gas emissions (GHG) – mean that the proportion of primary aluminum in the environmental indicators cumulative energy expenditure and carbon footprint is even higher than for cumulative raw material expenditure (93% and 97%, respectively).

By 2030, the negative environmental effects will also increase with the higher quantities of scrap used and thus also the higher post-dilution effects and losses. The cumulative raw material expenditure increases to 3.58–3.89 million t, the cumulative energy expenditure to 55.64–60.25 million GJ, and the carbon footprint to 5.63–6.11 million t in CO_2 equivalents for a 30% blend. For a 40% blend, the environmental effects increase to 4.78–5.18 million tons for the cumulative raw material expenditure. The cumulative energy expenditure increases to 74.05–80.33 million GJ and the carbon footprint to 7.51–8.15 million t in CO_2 equivalents. The percentage distribution of the proportions of primary aluminum and alloying metals changes only slightly because the weighting of the target alloys in 2030 also differs only slightly. In 2030, the proportion of primary aluminum in all three indicators will be even slightly more pronounced than in 2016. However, these increases are in the decimal range.

4.3 WP3 Analysis of innovative processing and sorting techniques, performance of sorting trials

The recovery of scrap that is as pure as possible, especially with regard to the relevant alloying elements, is a basic requirement for reducing downcycling, saving primary raw materials and reducing the environmental impact. In addition to sensible collection systems or a product passport, which has been under discussion for some time, this requires a deep understanding of sorting and analysis techniques. In the “OptiMet” project, a comparison of various analytical measuring methods (e.g., camera/sensor systems) available on the market today and their combinations was used to determine which analysis or sorting processes in combination with upstream or downstream separation processes (e.g., magnetic separation, fluidized bed, compressed air) make sense for mixed scrap fractions in order to ensure high qualities of secondary raw material and to gradually reduce unwanted downcycling. The analytical and technological limits with regard to the large number of alloying elements have been worked out.

WP3 thus focused on two main areas: First, various sorting methods for characterizing multi-material alloys of four different major metals specified by UBA were evaluated and compared. The analytical methods used were X-ray fluorescence spectroscopy (XRF), X-ray transmission analysis (XRT), laser-induced plasma spectroscopy (LIBS), and neutron activation analysis (NAA). Based on our assessment that imaging reflectance spectroscopy (HSI) in different wavelength ranges can also be used to better characterize the elemental composition of material streams, this was also considered. To make it clear: These sorting processes or analysis methods, which precede the actual separation process, are decisive for improving the separation factor or the quality of the overall process. The separation processes upstream or downstream of the sorting process (e.g., magnetic separation, sifting or compressed air) have only a negligible influence on the quality of the overall process. Experience from the recycling industry shows that this is less than 5%. In our investigations, mistakes amount to 3%.

Table 3: Evaluation of the individual analysis methods with regard to qualitative and quantitative criteria.

	pXRF	WDXRF	XRT/CT	LIBS	NAA	HSI
Detection limits	0.2 wt%	0.05 wt%	low wt% range	0.02%	ppm range	5 wt%
Depth of penetration	20 µm	50 µm	radiating	100 µm per shot	radiating	1 µm to 10 mm
Precision	high	high	low/medium	high	high	low (for metals)

	pXRF	WDXRF	XRT/CT	LIBS	NAA	HSI
Throughput	low (1 m2/h)	off-line, low (0.1 m2/h)	high, (low in CT mode)	medium (70 m2/h)	off-line, low	high (700 m2/h)
Effort/cost	low	high, complex sample preparation	medium, high initial costs	medium (high calibration effort)	medium, high initial costs	low

The criteria we evaluated and presented in Table 3 are mainly economic (effort, throughput) and metrological (penetration depth, accuracy, detection limits). In general, for the metal analysis methods evaluated, expensive, stationary instruments operating either off-line (WDXRF) or in-line (LIBS, XRT) have higher accuracy and lower detection limits. That means that these can reliably detect more elements in smaller traces. However, these capabilities can be fully taken advantage of only if a complex sample calibration or sample preparation is carried out beforehand. For example, the quantification of material streams with LIBS shows great weaknesses when an inhomogeneous mixed scrap stream is to be analyzed. This method requires extensive matrix correction, which is highly complex, time-consuming, and costly for such mixed scrap, which can contain up to 20 different chemical elements. There are approaches for calibration-free WDXRF and LIBS analysis of solids based on physical laws and calculations. However, these are not (yet) available for such complex material streams from mixed alloy scrap. Another important point is the required measuring time for a reliable detection or at least a differentiation of the individual pieces. Measurement time is directly linked to throughput, which is eminently important to the economics of an analysis and sorting process. The faster in-line analytical methods such as LIBS or HSI allow higher throughputs and are less susceptible to inhomogeneous samples. However, these have the disadvantage of lower accuracies and thus an increased risk of misidentification/sorting. In particular, HSI is not suitable for metals in the visible and near-infrared range for element quantification. Instead, they should be used for phase discrimination.

Another point of consideration is the depth of penetration: While the XRF methods, HSI, and LIBS analyze only the surface of a sample and may thus capture a non-representative sample, NAA and XRT are radiographic methods. These can detect the composition of the volume flow averaged from all three dimensions. In the case of the slow CT variant of the XRT, three-dimensional distributions of individual pieces can also be created. However, this is less interesting for recycling than for research or quality control of the microstructure of newly produced metal alloys. Using (PG)NAA, three-dimensional averaged chemistry of inhomogeneous samples is obtained. The measuring system offers advantages over existing methods, especially when rapid and representative analysis of large-volume samples is required. On the other hand, this technique does not (yet) have in-line capability and the evaluation of the measurements is quite complex. It is thus not standardized. In addition, especially in the analysis of steels, greater uncertainties can occur in the quantification of alloy supplements, which are due to the measurement setup.

The cost of an analytical method also plays an important role – both for the purchase of the instrument and for its maintenance and the corresponding personnel required. In this case, pXRF performs quite well because the instrument, including suitable calibrations, is available at quite reasonable prices, and the analysis itself requires hardly any sample preparation. The use of WDXRF and LIBS instruments is associated with higher acquisition costs as well as (in the case of WDXRF) considerably higher personnel requirements for sample preparation and data evaluation. At the high end of the cost scale are the XRT and PGNAA devices. PGNAA devices are not yet routinely available for recycling applications. In terms of initial cost, simple XRT instruments are comparable to WDXRF and LIBS analyzers. However, mixed scrap with highly variable compositions requires more sophisticated models that operate with two detection energies (duel-energy XRT).

Our research makes it clear that there is currently no all-encompassing analysis or sorting method for complex post-consumer mixed scrap that allows quick and easily measurements quickly and affords high accuracy yet is inexpensive and has no problems with the diversity of scrap streams. The market is segmented, and there are customized individual solutions. Close attention must therefore be paid to how meaningful the respective results are before and during their use. We therefore believe that a combination of analytical or sorting methods (e.g., LIBS for the light element components of aluminum and steel scrap coupled with XRF for the main alloying elements) should be sought if progress is to be made in the quality of recycling. Imaging techniques such as HSI can provide preliminary identification in this regard. This is subsequently refined by element-specific detection (e.g., XRF).

The selection of the analysis or sorting method depends on the alloying elements or impurities to be determined as well as the alloy type. There is not **ONE OPITMAL METHOD** for all elements and every alloy type. And there is not **ONE OPTIMAL SORTING EFFICIENCY** for all alloys and the methods considered. The specific use and target must be known in each case. Accordingly, the methods are defined and the sorting efficiencies predicted. Decision support is provided by the large number of studies conducted in WP3 and discussed in detail in the report.

Table 4: Factors (measure of sorting efficiency) for the detection of an element in an alloy type (steel, aluminum, copper).

	Sample	Method	Fe	Cu	Sn	Cd	
Steel	Reference alloys	Factor LIBS		0.65	< LOD	< LOD	
	Reference alloys	Factor pXRF	1.00	1.96	< LOD	< LOD	
	Reference alloys	Factor WDXRF	0.99	0.72	< LOD	< LOD	
	Scrap LIBS	Factor pXRF		2.70	< LOD	< LOD	
	Scrap NAA	Factor pXRF	0.98	1.27	0.19	< LOD	
			Al	**Fe**	**Si**		
Al	Scrap LIBS	Factor pXRF unpolished	0.87	9.52	14.14		
	Scrap	*Factor pXRF averaged (NAA + sparkOES)*	0.85	1.47	6.39		
	Scrap	*Factor LIBS averaged*	1.00	1.69	1.90		
	Scrap	*Factor WDXRF*	0.91	1.14			
			Cu	**Zn**	**Pb**	**Ni**	**Sn**
Cu	Reference alloys	Factor pXRF averaged	1.00	1.00	0.89	0.98	1.22
	Reference alloys	Factor WDXRF averaged	1.00	1.01	0.89	1.01	1.30

They always refer as a ratio the values of one method to another.

Two possible interpretations of the experimental results from WP3 should be mentioned for general comprehensibility and to explain how the results were handled. The first example is oriented towards sorting efficiency in terms of element detection (alloying elements or impurities). Table 4 lists the factors for the detection of an element in an alloy type (steel, aluminum, copper). They always refer to the ratio of the values of one method to another.

Explanation of the example Al scrap and Si content: Comparing the pXRF method with the reference method (spark spectrometry) results in a value 14-fold (overestimated) higher than for an unpolished scrap sample. In contrast, "only" 6.4-fold more silicon was detected for a polished sample. In comparison, the LIBS method is much better because it immediately results in a factor of 1.9 with unpolished samples, (i.e., it overestimates the result by only 90%). In the specific case, it is approx. 3.5-fold more accurate with respect to the true measured value. Thus, using LIBS instead of pXRF, the Si content in Al scrap can be detected 3.5-fold more accurately. This means that downcycling, which is based on incorrect concentration determination because (as the studies show) the method is unsuitable for this application, can be reduced by 1/3.5 (i.e., by approx. 72%) using LIBS as the analytical method. If this result is combined with the mistakes during separation (max. 5%), downcycling for Al scrap can be reduced by 71% overall or functional recycling can be increased accordingly. This applies when silicon is the impurity and alloys with too high a proportion of Si can be specifically separated using the appropriate method.

Table 5: Exemplary sorting efficiencies on mass and concentration changes of selected elements in Al and steel alloys depending on the method used and limit value specified.

		Fe < 1 wt%		Fe > 1 wt%	
	Method	**Fe %**	**Mass %**	**Fe %**	**Mass %**
Al alloys	LIBS	−29.67	15.06	167.19	84.94
	pXRF	−28.93	13.97	178.11	86.03
	WDXRF	−28.43	13.26	185.91	86.74
		Mg < 2.5 wt%		**Mg > 2.5 wt%**	
	Method	**Mg %**	**Mass %**	**Mg %**	**Mass %**
Al alloys	LIBS	−31.36	10.36	270.86	89.64
	pXRF	−1.72	0.32	518.84	99.68
	WDXRF	−12.20	3.37	348.73	96.63
		Cu < 0.5 wt%		**Cu > 0.5 wt%**	
	Method	**Cu %**	**Mass %**	**Cu %**	**Mass %**
Steel	LIBS	−95.81	64.5	52.73	35.5
	pXRF	−94.09	32.64	194.2	67.36
	WDXRF	−96.09	68.49	44.22	31.51

Negative changes in concentration show a relative reduction or depletion of impurities compared with the initial composition may be released to. Accordingly, a positive change indicates a relative enrichment of impurities in a fraction. The masses refer to the separated fractions. The following sorting criteria (limit values) were used as examples: Mg 2.5 wt%, Fe 1 wt%, and Cu 0.5 wt%.

The second example describes the sorting efficiency with respect to a given threshold value of a certain element in order to describe the separation of high and low impurity fractions.

For this purpose, Table 5 lists exemplary calculations and sorting efficiencies for the changes in mass and concentration of selected impurities or alloying constituents in aluminum and steel alloys depending on the method used and the specified limit value. Negative changes in concentration show a relative reduction or depletion of impurities compared with the initial composition. Accordingly, a positive change indicates a relative enrichment of impurities in a fraction. This means that the impurities can be either enriched or depleted in different fractions according to the specified limit value depending on the method used. This, in turn, is also an important step toward functional recycling or the minimization of downcycling.

Limit values that actually play a role in the recycling of alloys and are among the frequently present samples and impurities (Mg, Fe in aluminum alloys) or from pyrometallurgical considerations (Cu in steel) were selected. Depending on how the limit and sorting (approximation to the limit of smaller or larger contents) are chosen, different contents and masses of the resulting fractions will result. Limitations beyond this result from the separation process (e.g., by compressed air) used after characterization (5%). The methodological deviations were taken into account.

The result for this specific example is as follows: With a selected upper limit of 1 wt% Fe in Al alloys, the use of LIBS reduces Fe by approx. 30% – with a mass reduction of approx. 15%. In this case, the choice of measurement method is irrelevant because all methods investigated show similar calculated sorting results. For the approach to the limit “from above” (i.e., from higher values), a similar picture with only minor differences between the methods emerges.

On the other hand, for Mg in Al alloys at a chosen maximum limit of 2.5%, the methods differ considerably. For LIBS, which has the lowest analytical deviations (compared with the spark spectrometer), the sorting results are an approx. 31% reduction at a mass of 10% of the feedstock, whereas the concentrations and mass separations change little for pXRF or WDXRF. Accordingly, for the mass separations, for high concentration changes, only low values result because only individual pieces are separated.

For copper in steels, the enrichment is similar for the methods studied. However, the resulting masses differ slightly. LIBS and WDXRF have similar values and are thus not suitable for this application. Here, as in many other cases, pXRF is the method of choice. For the “from above” approach, there are hardly any mass reductions in the fractions. Only LIBS shows a change of approx. 90% of the initial mass with 270% higher Mg contents.

In summary, it can be stated: In order to considerably reduce downcycling and to recycle in a way that preserves quality and function as far as possible, it is necessary to determine the alloying elements precisely and to convert them into corresponding selective (narrow concentration ranges) fractions according to the target alloy. In most cases, the pXRF method shows the best results. In the case of aluminum alloys, the impurities are well detected by LIBS.

The reduction in downcycling can be expected to be on the order of **at least 70%** if, for example, pXRF is widely used in the recycling industry. Improved presorting reduces the measurement effort and thus the amount of data generated in the subsequent step and contributes to a further improvement of the qualitative recycling.

Ideal-typical process chain

Based on the tests and discussions with experts on the analysis and sorting of metal scrap, an **ideal-typical process chain** for the stepwise separation of mixed scrap has emerged. The starting point is an aluminum post-consumer mixed scrap (e.g., e-waste), which is rich in aluminum but also contains appreciable amounts of copper, iron, zinc, and silicon, among other elements.

At the beginning of the process chain, there is then a rough manual (visual) pre-sorting, whereby the expert knowledge of specialists at the recycling centers or collection points is crucial. A hand-held XRF is often used at this stage. After subsequent shredding of the pre-sorted fractions, plastics and other organic components such as wood are separated via an air classifier in an initial step. Using suitable analytical methods (e.g., HSI and XRF), the plastics are then separated into fractions that are as pure as possible so that they can be reused – usually in granulate form.

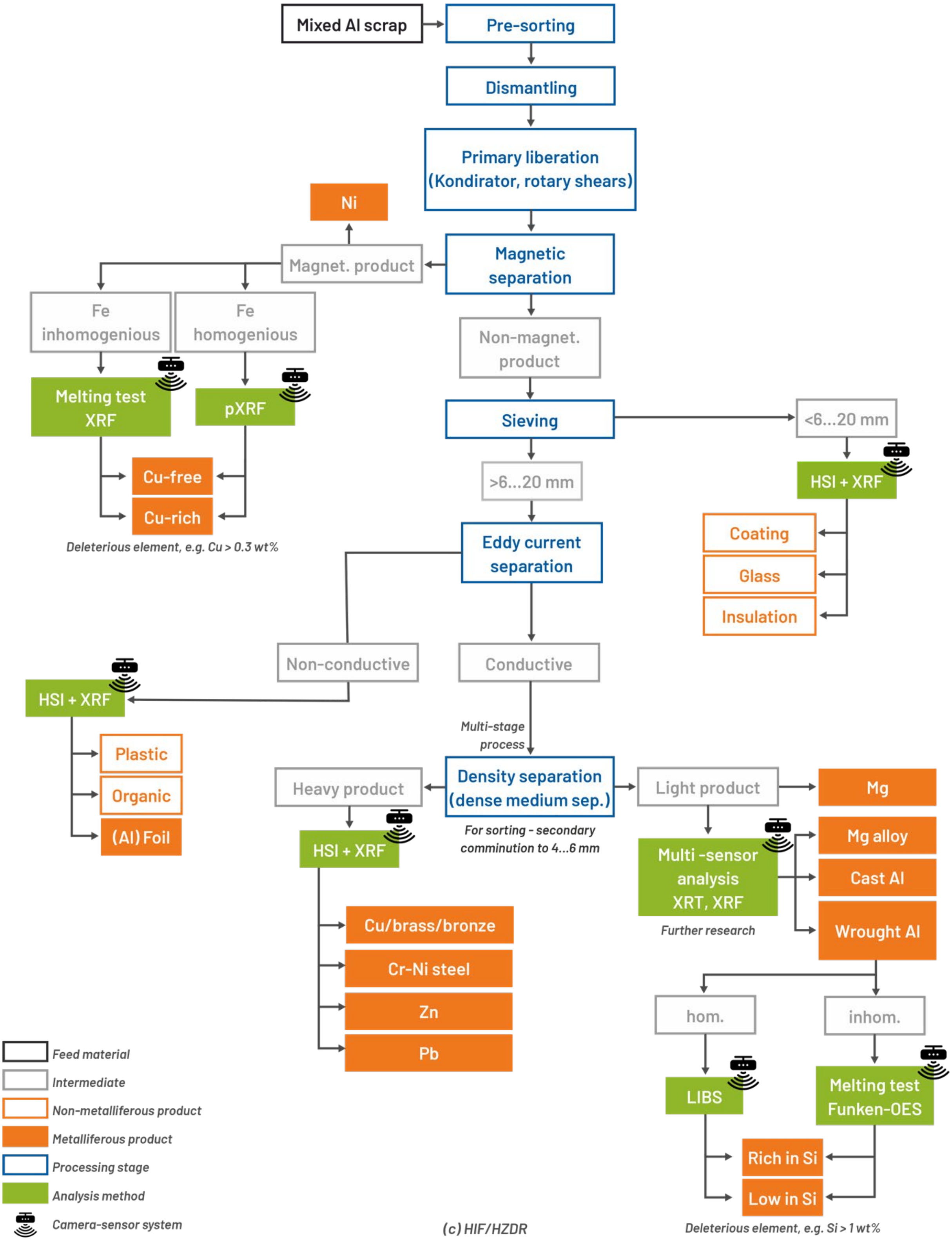
The remaining part goes to the next process step. In our example, this is density separation. In this step, light and heavy metal fractions are separated from each other. Magnetic separators are then used to separate iron (magnetic) and non-magnetic metal fractions. The Fe fraction with the corresponding impurity contents is separated into low-impurity (e.g., Cu-free) and high-impurity (e.g., Cu-containing) fractions by XRF.

The non-magnetic fraction is subjected to sieve classification and eddy current separation in order to separate stainless steel, non-ferrous metals and light metals in a subsequent step.

This is precisely where current research comes in. This is because sorting into fractions such as stainless steel or cast Al alloys can **no** longer be done using only **one** analytical method such as LIBS or XRT. At this point, the desired selective separation into Si rich and Si poor fractions requires multi-sensor systems (i.e., a combination of different methods). After an evaluation of all results, the combinations that seem reasonable to us can be taken from the detailed report. Further underpinning was not the content of the project. However, taking into consideration an example of mixed Al scrap available in the final report (Figure 3) makes it clear at how many points sensor/camera systems will have to be used in order to actually be able to reduce downcycling and recycling in a function-preserving manner. The final step is the further processing of the correspondingly separated fractions. This can be either pyro- or hydrometallurgical or chemical processing.

Particularly in the analytical methods (multi-sensor analyses) and the couplings to the corresponding (pre-)sorting or separation steps, there is still a considerable need for research and development both in terms of sensor development (measurement in real time) and the integration and creation of fully interconnected pre- sorting-sensor-separation systems.

Figure 3: Example of an ideal process chain for Al mixed scrap



Source: HIF HZDR, adapted from H. Martens et al; Recyclingtechnik, Springer, 2016

4.4 WP4 Evaluation

In WP4, the results of the sorting or analysis tests from WP3 and the improved sorting efficiencies derived from them are transferred to the volume model of 2030 in WP2, thereby illustrating the savings effects. This concerns the part of the total volume that is not well-defined production waste and therefore already easily separable in pre-sorting but which, despite pre-sorting, still goes into further processing relatively mixed (e.g., WEEE). These include mixtures of wrought aluminum alloys with a high aluminum content (> 99%), cast aluminum scrap with high silicon contents, and scrap containing a high titanium content but only a low aluminum content (< 10%).

The sorting and analysis tests in WP3 start with pre-sorted scrap, and the sorting efficiency determined from this always refers to this initial quality. For example, a sorting quality such as non-ferrous metal in which copper alloys are mixed with brass and individual aluminum scrap parts or stainless steel in which every scrap part of the sample consists of scrap with a high chromium content but pure chromium steel is still mixed with chromium-nickel steel and other stainless steels.

For the calculations in WP4, the results of the combined and coupled use of pre-sorting by magnetic separators and eddy current separators and manual shape sorting combined with the analysis and sorting technologies (e.g., LIBS, pXRF) were used first. High sorting efficiency improvements were determined for most alloying elements.

Sorting efficiencies and environmental indicators

By applying analysis and sorting methods such as pXRF and LIBS downstream of presorting, improved sorting efficiency of Si- and Ti-rich aluminum alloys of 26.3% (pXRF only) and 89.0% (pXRF + LIBS) can be achieved on average. A particularly high percentage increase in sorting efficiency is obtained with pXRF for the alloying element titanium. Losses in the production process of new alloys from mixed scrap decrease by about 14% as a result of the improved sorting of aluminum scrap fractions.

This percentage change is reflected in the environmental assessment indicators. The total cumulative raw material expenditure of all elements is reduced from 5.18 million t to 3.76 million t when using pXRF and a blend ratio of 40% because of improved sorting efficiency. The total cumulative energy expenditure decreases from 80.33 to 59.20 million GJ and the carbon footprint from 8.15 to 6.02 million t CO_2 equivalent. The three environmental indicators thus improve by almost one quarter compared with the status quo for each quantity model because of the improved sorting or analysis technique with pXRF: Cumulative raw material expenditure: −27.6%, cumulative energy expenditure −26.3%, and carbon footprint −26.1%.

Thus, based on the assumptions selected here, by using pXRF, compared with the status quo, about 59,200–85,600 t of material and 1.5–2.2 million metric tons of CO_2 can be saved in 2030 for Germany alone depending on the degree of mixing and the particular scenario (Table 6).

Table 6: Overview of sorting improvements for aluminum and derived carbon footprint savings for Germany 2030

Scrap category	Status quo (WP2)	Sorting improvement pXRF	Sorting improvement pXRF + LIBS	Change in sorting improvement pXRF	Change in sorting improvement pXRF + LIBS
AL 30% mixed 2030 min					
Post-dilution in t	224,644	165,489	24,743	− 59,155	− 199,901
Loss in t	390	335	335	−55	−55
Carbon footprint post-dilution + losses (in 1000 t CO_2 equivalents)	5,634	4,163	640	−1,471	−4,994
AL 40% mixed 2030 min					
Post-dilution in t	299,525	220,652	32,991	−78,873	−266,534
Loss in t	520	447	447	−73	−73
Carbon footprint post-dilution + losses (in 1000 t CO_2 equivalents)	7,513	5,550	853	−1,963	−6,660
AL 30% mixed 2030 max					
Post-dilution in t	243,695	179,524	26,841	−64,171	−216,584
Loss in t	423	364	364	−59	−59
Carbon footprint post-dilution + losses (in 1000 t CO_2 equivalents)	6,112	4,514	694	−1,598	−5,418
AL 30% mixed 2030 max					
Post-dilution in t	324,927	239,365	35,789	−85,562	−289,138
Loss in t	564	485	485	−79	−79
Carbon footprint post-dilution + losses (in 1000 t CO_2 equivalents)	8,150	6,021	925	−2,129	−7,225

Reduction of downcycling

Here, a result for aluminum alloys with the accompanying elements iron and silicon and the methods LIBS and pXRF is explained as an example.

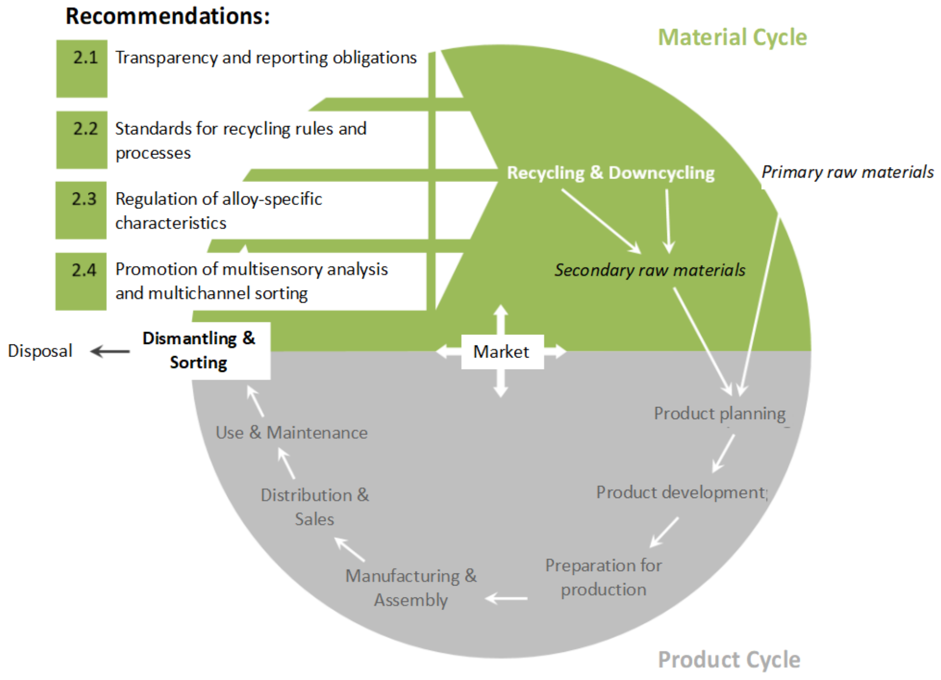
The measured values in WP3 clearly show how the actual contents can be either overestimated or underestimated depending on the method used. For example, LIBS leads to an excellent detection of aluminum but overestimation of silicon concentration in aluminum alloys by a factor of 1.9 (90%). In this case, the pXRF method is still well above this but is the method of choice for many other (heavier) alloying elements. The post-dilution effort for the main alloying elements determined for this case changes considerably (i.e., > 90%), especially when **combining the pXRF and LIBS methods**. The savings effect with pXRF alone amounts to 59.2–86.6 kt of primary raw materials and, in combination with LIBS, is 200–289 kt in 2030.

Consequently, with the considerably lower post-dilution effort when pXRF is used in combination with LIBS, the values of the environmental assessment indicators will also decrease assuming widespread application of these methods in the recycling industry in 2030. Thus, not only 1.5–2.1 million t CO_2 emissions but rather 5.0–7.2 million t can be avoided if both methods are used in combination.

4.5 WP5 Recommendations for action

Based on the results of WP1 to WP4, suggestions are made as to how the concepts we have developed can be anchored in the metal recycling industry in order to leverage the potential identified and for the widespread dissemination of alloy-specific sorting. The primary objective of these recommendations for action is to establish the highest possible quality of functional recycling of metallic alloys and their accompanying elements and to avoid downcycling.

Figure 4: Presentation of material cycle and political fields of action



Source: Own graphic, TU Dortmund

Product design and product passport

One of the main requirements is to pay attention to recyclability as early as the product design stage. This includes **easy disassembly** (Figure 4) so that products can be easily dismantled into their individual components after their useful life (EoL). However, this also entails ensuring that products consist of as few types of alloys as possible or metals with as few impurities as possible. This simplifies the uniform separation and reduces losses of accompanying elements in the pyrometallurgical process. A **product passport** with the necessary information for the recycler could also simplify functional recycling.

Transparency and duty to report

It is necessary to establish a reliable and comprehensive **data basis** based on continuous surveys of alloy-specific material streams and raw material losses. Thus, weak points and hot spots have to be identified as well as important data such as quantity, composition, demand, limits, quotas, and target values. For well-founded decisions by relevant actors in science, politics, and the recycling industry, material streams from dismantling, sorting, and recycling must be determined, documented, and reported in a standardized and continual manner.

Definition of downcycling, purpose, and quality

The heterogeneous and unclear definitions of recycling and downcycling reduce motivation to recycle in a way that preserves function. Appropriate suggestions for defining downcycling are provided in the report.

It is also important to clearly define the concepts of "purpose" and "original purpose," (e.g. in AbfallRRL, KrWG, and AltfahrzeugRL. It must be made clear which range of applications recyclates will have and in which products and in what proportion they are to be found. For this reason, the purpose of recycling as well as a mandatory substitution rate that adapts to technological progress must be defined for new products.

To date, there is no universal measure of material quality to which a definition of downcycling can refer. This means that downcycling must be made quantifiable because this is the only way to identify the extent of downcycling effects and take them into account in technological developments in order to avoid downcycling. Downcycling must be anchored as a phenomenon within the framework of the recycling targets in such a way that it is avoided as far as possible by means of incentive systems.

Substitution rate

The goal of implementing high masses in recycling makes the objective of the finest possible separation and sorting depth – and thus the avoidance of downcycling effects – recede into the background. Calculating recycling rates is not sufficient in this context. Although they show the collection rate of recyclable material, they do not indicate how much recycled material actually flows back into the economic system. A substitution rate that indicates the ratio of recycled raw materials used in relation to the total material input used (primary raw materials and recycled raw materials) is more target-oriented. In particular, the substitution rate should determine the amount of material or raw material that is found as a recycled raw material in new high-value products. This would automatically reduce downcycling.

EU-wide harmonization of recycling rules, standards, and procedures

The standardization of recycling rules with simultaneous EU-wide cooperation is important in order to be able to minimize current raw material losses (including through downcycling). An EU-wide standardization of recycling rules and procedures supports the assurance of functioning internal recycling markets and functional recycling. There are currently considerable differences in the process quality of recycling within the EU in terms of recovery and quality of recyclate, reuse, pollutant removal, process emissions, safety and environmental standards, and enforcement of waste legislation. This results in outflows of waste to countries with only voluntary application and recycling processes that are not as good. Important recyclable materials are thus lost not only to the domestic market but in principle.

Transparency is achieved based on a uniform understanding of the recycling process as well as recycling targets (e.g., quotas). In addition, losses of all kinds, including quality, are minimized by stimulating an overarching and networked optimization of recycling. Standardization must not stand in the way of efficient recycling tailored to specific requirements. The goal must be mandatory standards and technical specifications that take into account and further develop the state of the art in recycling technology along the entire value chain while also considering the environment, health, and process efficiency.

The specialization of individual companies in certain main metals can also lead to the avoidance of downcycling effects by transporting the individual metals, alloys or elements to specialized recycling yards and processing them there. The challenge can be met by encouraging strategically located recycling companies to specialize and to network with less specialized companies. Such specialized recycling solutions are offered by companies such as Aurubis AG, Panizzolo S.r.l., Barradas GmbH and Recuperma GmbH.

Harmonize alloy designations across the EU and reduce diversity

Alloy designations and numbers must be standardized – and, above all, harmonized throughout the EU – in order to increase the traceability of alloy-specific material streams. Existing designation standards apply either nationally, at the European level, or worldwide. The objectives of standardization should be to ensure quality assurance, safety, and environmental protection as well as a better understanding of this between industry, technology, science, and administration.

For example, it is debatable whether more than 2000 different steel alloys are actually needed. The variety of unnecessary alloying elements should be minimized in order to avoid downcycling.

Research and development for process engineering optimization

In order to ensure high-quality recycling, alloy-specific material streams must be separated from each other with the highest possible sorting depth with regard to the accompanying elements. This is possible only to a limited extent with the sorting and separation processes currently available on the market. In this context, it is recommended to replace binary single sorting methods by multi-channel, multi-stage sorting. Scientists and sensor developers are called upon to improve metal recycling with innovative multi-modal in-line analysis and sorting techniques, among other things, in order to enable the real-time detection of impurities. Corresponding technological developments should be supported financially.

Lighthouse projects

The financial support of strategic lighthouse projects that pursue the goal of an innovative and “ideal process chain” of collection, disassembly, sorting, separation, and reprocessing is another political instrument to counteract downcycling. Because of their size and publicity, such projects can serve as a guide. The aim is to create public awareness of recyclable materials as well as the recycling and sustainable use of these materials. Consumption decisions are thus supported in the direction of circular solutions. Cooperation between product developers, manufacturers, and recyclers plays an important role here. Although recommendations for action pursue goals and potential opportunities, risks, obstacles, and challenges are also to be expected with the implementation of these measures. These are compared and ranked for an overall assessment (Table 7).

Table 7: Overall assessment of the political recommendations for action

Political recommendations for action	Opportunities/goals	Risks/challenges
2.1 Transparency and duty to report	• Reliable data basis for political decisions (e.g., setting limit values) • International networking through cooperation • Creating awareness of alloy-specific material streams and losses through transparency	• High expenditure for companies in the production, disposal, and processing of metal alloys • High effort of standardization and introduction of a suitable documentation procedure • Necessity of the widespread use of modern analytical technology
2.2 Standardization or standards for recycling rules and procedures	• International cooperation for the adaptation of standards and common objectives • Unified understanding of recycling and downcycling to encourage international closed-loop recycling • Comparability of key figures (e.g., recycling rates)	• Lack of specialization of recycling centers • High effort of standardization and harmonization in regulations
2.3 Regulation of alloy-specific properties	• Market-based incentives to optimize products, material streams, and process methods in line with targets (e.g., reduction of alloying elements that do not belong to the starting alloy) • Reduced dependence on imports through the use of recycled materials • Economic and social attention through public transparency	• High research effort on substitution possibilities • High effort of optimization of products regarding possible limitation in functionality • High effort of verification (e.g., REACH)
2.4 Promotion of multi-sensory analysis and multichannel sorting	• Increased sorting efficiency and increased sorting success to avoid downcycling effects • Strengthening of the research and industrial location through the use and optimization of state-of-the-art sensor and separation techniques • Increased attention and awareness of society • Creation of a transparent database in order to increase efficiency and find solutions for weak points • Creation of market-based incentives for high sorting success and high-quality recycling	• Cost of obtaining financial resources for the promotion of technical equipment and trained personnel • Risk of misinvestment as a result of the poor utilization of technologies • Risk of overregulation of the market • Challenge of system and infrastructure adaptation

5 Outlook

Within the framework of WP1 to WP4, recommendations for action for politics, science, and economy were elaborated at both the national and international level. These are based on a predominantly self-collected and thus reliable data basis. The focus was on recommendations for action that address, in particular, the scientific and technical challenges of the functional recycling of metallic alloys. The focus was on how primary raw materials can be conserved as diluents in the recycling process, how downcycling can be reduced, and how functional recycling can be ensured. The scientific-technical further development of innovative alloy-specific sorting and separation processes based on combinations of camera/sensor systems and the establishment of these modern methods in the recycling industry is one of the essential pillars for considerably improving the current situation. The recycling-friendly design of materials, products, and goods is a second pillar for avoiding subsequent downcycling and, in addition to the necessary legal framework conditions, forms the basis of a functioning circular economy. This requires close exchange between material and product developers and recyclers as well as an increased awareness of recyclables as well as the recycling and sustainable use of these. Consumption decisions are thus supported in the direction of circular solutions.