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ILESA - Smart steering of waste streams containing precious and minor metals: pooling, temporary storage, recovery rate

Final Report (Brief version)

For our Environment

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ILESA - Smart steering of waste streams containing precious and minor metals: pooling, temporary storage, recovery rate

Final Report (Brief version)

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Abstract

Minor metals such as neodymium and other rare earth metals, indium or tantalum are not recovered at all from post-consumer waste or only to a limited extent. This is partly due to the fact that many of the products containing such metals have not been on the market for long, so that both the development of large-scale recycling processes has not yet taken place and the return volumes are still too low. For the recovery of precious metals from waste, proven processes have been available for many years. However, their efficient collection and separation, even from low-concentration waste streams from a large number of small sources, poses a challenge. Moreover, the concentration or quantity of precious and minor metals in waste products or components is often so low that their collection or separation from the waste streams currently is not profitable.

The investigation focused on the waste streams NdFeB magnets, vehicle electronics, precious metal-containing environmental catalysts, cerium- and lanthanum-containing waste streams, rare earth metal-containing phosphors, indium-containing LCD layers and tantalum capacitors.

For these waste streams, it was investigated how novel logistics concepts and approaches to intelligent organisation and the design of material and information flows can improve the recycling. Technical, organizational, and legal possibilities for the longer-term interim storage of such waste, until large-scale recycling capacities are available, were specified and examined. Finally, ways to estimate an environmentally optimal recovery rate were developed and proposals for measures to achieve more recycling were developed and evaluated.

Kurzbeschreibung

Sondermetalle wie Neodym und weitere Seltenerdmetalle, Indium oder Tantal werden in Deutschland heute nicht oder nur in sehr eingeschränktem Maße aus Post-Consumer-Abfällen zurückgewonnen. Dies liegt zum Teil daran, dass viele der Produkte, die solche Metalle enthalten, noch nicht lange auf dem Markt sind, so dass sowohl der Aufbau von großtechnischen Recyclingverfahren noch nicht erfolgt ist als auch die Rücklaufmengen noch zu gering sind. Für die Rückgewinnung von Edelmetallen aus Abfällen gibt es zwar seit vielen Jahren bewährte Verfahren, eine Herausforderung stellt jedoch ihre effiziente Erfassung und Separation auch aus gering konzentrierten Abfallströmen aus einer Vielzahl kleiner Anfallstellen dar. Die Konzentration bzw. die Menge an Edel- und Sondermetallen in Altprodukten oder Bauteilen ist zudem häufig so gering, dass ihre Erfassung oder Separation aus den Abfallströmen aktuell nicht wirtschaftlich ist.

Die Untersuchung befasste sich schwerpunktmäßig mit den Abfallströmen NdFeB-Magnete, Fahrzeugelektronik, edelmetallhaltige Umweltkatalysatoren, cer- und lanthanhaltige Abfallströme, seltenerdmetallhaltige Leuchtstoffe, indiumhaltige LCD-Schichten und Tantalkondensatoren.

Für diese Abfallströme wurde untersucht, wie neuartige Logistikkonzepte und Ansätze zur intelligenten Organisation sowie zur Gestaltung von Material- und Informationsflüssen das Recycling verbessern können. Es wurden technische, organisatorische und rechtliche Möglichkeiten zur längerfristigen Zwischenlagerung solcher Abfälle, bis großtechnische Recyclingverfahren verfügbar sind, konkretisiert und geprüft. Schließlich wurden Wege zur Abschätzung eines ökologisch optimalen Rückgewinnungsgrades erarbeitet und Maßnahmenvorschläge zur Erzielung von mehr Recycling entwickelt und bewertet.

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List of Abbreviations

AVV	German Ordinance on the European Waste List (Abfallverzeichnis-Verordnung - AVV - Waste Classification Ordinance)
CCFL	Cold Cathode Fluorescent Lamp
CO_2	Carbon dioxide
CRT	Cathode Ray Tube
EC	European Community
eq	equivalent
EU	European Union
FCC	Fluid Catalytic Cracking
FE	Ferrous materials
GWP	Global Warming Potential
ID	Identification
IDIS	International Dismantling Information System
ILESA	Project acronym: Smart steering of waste streams containing precious and minor metals (Intelligente Lenkung von edel- und sondermetallhaltigen Abfallströmen)
InAccess	Project acronym: Development of a resource-efficient and economic recycling process for LCD screens with particular consideration of the recovery of their indium content (Entwicklung eines ressourceneffizienten und wirtschaftlichen Recyclingprozesses für LCD-Bildschirmgeräte unter besonderer Berücksichtigung der Rückgewinnung des Indium-Inhalts), Research project on behalf of the Federal Ministry of Education and Research, FKZ 033R088
KEP	Courier, express and parcel services (Kurier-, Express- und Paketdienste)
LCD	Liquid crystal display
LED	Light emitting diode
LDL	Logistics service provider (Logistikdienstleister)
MinSEM	Project acronym: Concept for the recovery of rare-earth elements as well as platinum group metals from mineral treatment and production residues, current research project on behalf of the Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung - BMBF), FKZ 033R141
MRT	Magnetic resonance tomography
NdFeB magnet	Neodymium iron boron magnet
NiMH	Nickel metal hydride
ORKAM	Project acronym: Optimisation of the separation of components and materials for the recovery of critical and environmentally relevant end-of-life vehicle metals, research project on behalf of the German Environment Agency, FKZ 3713 33 337
PGM	Platinum group metals
RePro	Project acronym: Further development of extended producer responsibility under resource protection aspects using the example of electrical and electronic equipment. Re-

	search project on behalf of the German Environment Agency, FKZ 3711 95 318
ReStra	Project acronym: Determination of substitution potential of primary strategic metals through secondary materials. Short title: Recycling potential of strategic metals. Research project on behalf of the German Environment Agency, FKZ 3711 93 339
RFID	Radio-Frequency Identification
DIR	Directive (EU)
RERP	Recycling enterprise resource planning system
REM	rare-earth metals
USGS	United States Geological Survey
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
WEEE Directive	Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment

1 Summary and Assessment of Measures

1.1 Introduction

In Germany, minor metals such as neodymium and other rare-earth metals, indium and tantalum are currently not recovered from post-consumer waste, or only to very limited extents. This is partly because many of the products that contain such metals have not been on the market for very long, so that not only have large-scale, commercial recycling processes not yet been set up, but also the quantities of waste arising are still too small. Processes for the recovery of precious metals from waste have long been established on industrial scale. However, efficient collection and separation of these metals from waste streams, potentially with very low concentrations and from a large number of small sources, is a challenge. Very often, the concentration or quantity of precious and minor metals in waste products is so low, that their collection or separation from waste streams is currently not economically viable.

The study largely focused on the following waste streams: neodymium-iron-boron (NdFeB) magnets, vehicle electronics, environmental catalytic converters containing precious metals, waste streams containing cerium and lanthanum, phosphors containing rare-earth metals, LCD layers containing indium and tantalum capacitors. The study examined how, for these waste streams, new types of logistics concepts and approaches to intelligent organisation and the design of material and information flows can promote recycling. Technical, organisational and legal opportunities for longer-term interim storage of such wastes, until large-scale industrial recycling processes are available, were specified and assessed. Finally, ways of estimating an environmentally optimum recovery yield were worked up and measures for achieving more recycling were proposed and assessed.

1.2 Consolidation (Pooling) of waste streams containing precious and minor metals

1.2.1 Collection logistics concepts and design of information flows

The business logistics is a scientific discipline, which does not follow a uniform paradigm. The management of flow systems is an understanding of logistics that is currently taking hold, which offers empirically verifiable, successful guidelines on strategic planning as well as tactical decisions and the operative control of logistics systems. In general, as a business discipline, logistics is orientated on efficiency increasing mechanisms, which were successfully established in industrialisation. Logistics sees value-adding processes or recycling processes as a network of connected players/companies, who implement the overall process together. The networks are represented in node and link models. Nodes represent, for example, warehouses, stores and companies and links represent the connecting supply relationships. Such a model visualises the network and provides information about the number and properties of the nodes, if applicable their location relative to each other and about the interconnection of the nodes (links) as well as their properties. Logistics networks are multi-level. The levels focused on here are the physical level of the goods and the informational level for control of the physical goods level. Improvements of logistics processes can take place on both levels, in which case they each have a reciprocal influence on each other. The financial level was also examined. This provides incentive and motivation for entrepreneurial action.

The challenges in pickup recycling logistics differ in several aspects from those of distribution logistics in providing value-adding chains. The challenges in recycling chains were therefore assembled generically on the named levels and the respective approaches to solutions were described in detail. Table 1 shows an overview of the challenges and solutions, structured according to steps in the recycling chain and network level.

Table 1: Challenges and solution approaches along a generic recycling chain

	Collection point	Sorting and dismantling	Recovery
Physical level	Challenge: Problem of the first mile Time and material consolidation Organisation of container systems Fit-for-use handling in collection points **Solution:** Route planning for time (and material) consolidation as well as volume consolidation Shortening of the process stopping times	Challenge: Positioning of sorting and dismantling in the recycling chain Optimisation of manual processes to reduce unit labour costs **Solution:** Compilation and provision of dismantling information in the chain	Challenge: (Intralogistics) Storage close to production/treatment locations Storage of containers Logistical processing of co-products **Solution:** Allocation of supply and demand
Informational level	Challenge: Control of collection processes Triggering of pickups Quantity plannability Degrees of freedom for planning processes Reduction of stopping costs/stopping times **Solution:** Automation or partial automation of level indication Quantity plannability degrees of freedom for planning processes Digital spot market platform for pickup Notification to reduce stopping costs	Challenge: Identification of recoverables Information on accessibility for dismantling **Solution:** Auto-ID system for the identification of recoverables in components Open information platforms for information on the accessibility of the components Provision of validated dismantling instructions on (open) platforms	Challenge: (Control of the intralogistics) Planning of distribution of the products by allocating supply and demand **Solution:** Spot markets vs. cooperations
Financial level / Motivation/ Incentive	Challenge: Legal obligations Economic attractiveness Interaction of both aspects **Solution:** Award at market prices to logistics service providers, who are able to increase potential consolidation effects	Challenge: Increase in economic attractiveness by structuring the learning curve **Solution:** Targeted use of the experience curve	Challenge: Revenue optimisation vs. customer loyalty Logistic expenditures for by-products **Solution:** (Spot markets vs. cooperations)
	Coordination tasks of logistics as a cross-disciplinary function		

The "first mile" of waste management logistics, in the same way as the "last mile" of distribution logistics, is particularly challenging. The "last mile" in logistics describes the transport to the customer's "front door" and is characterised by a large number of widespread delivery points with small quantities per delivery. The "last mile" share of the total delivery costs is correspondingly high. In the same way, in waste management logistics, the "first mile" of the waste, from the potentially numerous collection points / dismantling facilities to the treatment plant, often with small quantities, is accompanied by large challenges.

If logistics is understood to be the management of flow systems, a significant efficiency gain lies in cross-company or cross-step coordination of process chains. Therefore, a model was also considered in which companies acting as system operators coordinate the entire logistics process, across all the individual steps. Several solution approaches indicated in the steps can be integrated into such a concept.

An essential pillar of logistics management is the availability of information. No, or very few, recycling chains currently exist for waste containing precious and minor metals considered here. Accordingly, hardly any historical values are available. One proposal is therefore to support the establishment of a software-based system which, on setting up a recycling chain, collects and stores data on logistics processes (especially movement and quantity data), in order to enable data-based iterative process improvements. These can take place in-house, but also across companies and steps in the coordination of whole process chains.

Other solution approaches can be represented in the proposed software system (Recycling Enterprise Resource Planning system, RERP) to achieve more efficient handling of the logistics. For example, the measurement of levels in collection containers, which could then be used to control pickup processes and for the planning of future pickup processes.

Equally, the potential of logistical consolidation can be assessed far better, if historical values of generated quantities can be evaluated with spatial information and movement data, and can be used for consolidation efforts. As this information is not yet available in an evaluable form, consolidation/pooling workshops should be held with practitioners, enabling their empirical values to be used.

1.2.2 Legal aspects of the separation and labelling of waste streams containing precious and minor metals

Obligations to dismantle components of waste electrical equipment or end-of-life vehicles containing precious or minor metals can and should be arranged at national and/or European level. The corresponding regulatory instruments regarding waste electrical equipment and end-of-life vehicles provide the opportunity to establish additional recovery targets for components containing precious and minor metals, which would have to be achieved by the manufacturers and/or the primary treatment plants/dismantling facilities.

In particular, it must be taken into consideration that the separation itself with subsequent interim storage of the components containing precious and minor metals, cannot be classified as part of the recovery or entering a recovery process and therefore cannot be considered in the recovery rates according to the Electrical and Electronic Equipment Act (ElektroG). There is no statutory deadline on when the recovery must be completed. Hence, the actual recovery which takes place after an interim storage can be taken into account in the recovery rates.

As (almost) no components containing precious and minor metals are recovered separately so far, and despite this, the recycling and recovery targets are achieved, it is possible that separation itself with subsequent interim storage of individual components containing precious and minor metals will not lead to problems in achieving the recovery targets in practice. However, if achievement of the recycling/ recovery targets due to increased separation and interim storage of individual components or groups of components until they are actually and finally recovered should become problematic in practice, an amendment to the ElektroG would be one option so that interim storage, at least of components containing minor metals would, by way of exception, be able to be classified as (possibly preliminary) recycling / recovery provided that the actual future recycling is assured. However, such an amendment to the national law is currently not in accordance with the requirements of the WEEE Directive, which explicitly does not recognise interim storage as recovery. If a change in the recovery definition is the objective, this would also have to be done at the European level and not only at the national legislation level.

1.2.3 Recovery processes, consolidation and information concepts

Magnetic materials containing rare-earth metals

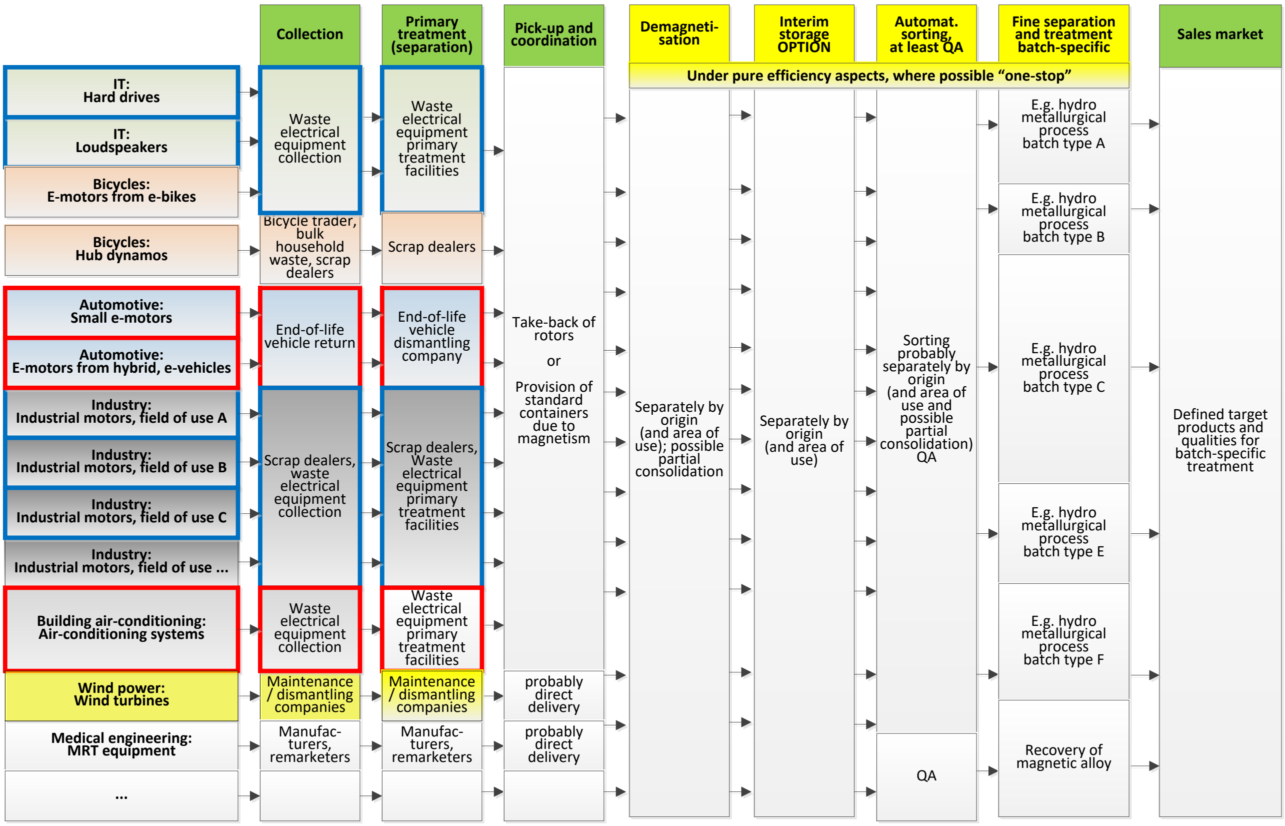
The implementation of recovery solutions is , first of all, hampered by the fact that in the waste streams with the largest quantity (currently hard disk drives) the quantity of magnets per individual device is very small, while waste streams with large individual quantities (e.g. wind turbines) currently have only a small total potential. However, a large growth in quantity is expected for electric bicycles, cars and air-conditioning systems. The potential actually available in Germany results from the quantities of magnetic material used in the applications, less the fractions that are exported or are disposed of improperly. In addition, material losses in the process chain must also be taken into consideration.

Overall, the largest cost factor is the dismantling of the magnets. For comparatively large magnets, however, economically viable dismantling, especially in larger companies, does not seem unrealistic in the long term. However, economically viable implementation of the whole process chain through to the production of marketable material fractions requires throughputs, which can probably only be achieved with growing waste streams with large potential quantities and volume consolidation.

In addition to the regulatory measures outlined, handouts for dismantling facilities on the transfer of lean management approaches to the disassembly processes can assist in the reduction of dismantling time and effort.

Figure 1 shows a potential rough process chain concept for the consolidation and processing of NdFeB magnets from different sources.

Figure 1: Rough process chain concept for the consolidation and treatment of NdFeB magnets from different sources; blue frames: currently dominant waste streams in quantity terms; red frames: rapidly growing volume streams



The necessary demagnetisation should be carried out by a central treatment company in large, efficient continuous furnaces. It must be ensured that no other types of magnets get into the process. In addition, the composition of NdFeB magnets varies substantially, so that sorting/grading or separate collection would appear almost indispensable for high-quality further processing.

A basic differentiation must be made between two types of consolidation: Consolidation in the picking up and consolidation in the treatment / preparation and processing. In the case of the pickup, joint transport of (labelled) quantities from different application areas but uniform points of waste generation generally reduces transport costs.

At which points in the process chain consolidation, i.e. mixing, should take place for treatment and processing of partial quantities, depends, among other things, on the size and uniformity of the partial quantities, the foreign substances they contain, the planned treatment method and the requirements for the quality of the secondary magnet material, as well as the requirements of the customer markets for the secondary materials and the level of the expected remuneration. Large magnets from large motors or wind turbines would therefore have to pass through adjusted process chains. Waste magnetic material that is generated in larger quantities and in a well-defined form and composition, could possibly be further processed directly, for example to produce secondary magnetic alloys. Instead of manual dismantling, mechanical or automatic separation methods should be used, especially for small magnets in large quantities (e.g. from hard drives).

Treatment through to separation of pure rare-earth metals or metal oxides requires very costly separation processes and realistically can only be achieved in an existing plant, possibly abroad. If they did not already operate such processes, central treatment companies for NdFeB magnets would limit themselves to the production of secondary magnetic alloys and/or rare-earth metal oxide concentrates, which are then passed on to treatment specialists for rare-earth metals.

Interested players could occupy a largely unoccupied, foreseeable growth market, especially as soon as waste products with large magnets are disposed of in larger quantities. However, the risk of recovering the investment costs remains. It is questionable what remuneration would have to be paid to the primary treatment facility, in order to secure the required delivery readiness and delivery quality. Willingness to purchase and the conditions of the recycler of rare-earth metal concentrates, or rather price fluctuations on the raw materials market are factors that are almost impossible to predict. Changes to magnet recipes or product designs can also jeopardise the business. Despite all difficulties, implementation seems feasible.

Regulatory measures can have a supporting effect. In particular, the following are feasible:

- An obligation to label motors with NdFeB magnets, which contain individual magnets from a defined minimum mass.
- An obligation to separate magnets which are known or identifiable as such as well as from labelled motors and equipment and to recycle them.
- The obligation to install NdFeB magnets so that they can be easily dismantled, provided there is no conflict with energy and material efficiency targets.

End-of life vehicle components containing precious metals

The quantity of printed circuit boards per end-of-life vehicle spread throughout the electronic components can be estimated to be approx. one kilogram. However, not all printed circuit boards and electronic components by far can be removed with justifiable effort. Another obstacle is that only a small quantity of vehicle electronics or lambda oxygen sensors occurs at each end-of-life vehicle dismantling facility. Treatment processes for waste electrical and electronic equipment, which are largely already available, can be used to separate precious metal containing fractions from electronic components. Initially the components containing printed circuit boards can be dismantled manually. Then their cases can be broken open to gain access to the printed circuit boards they contain, for example, in impact mills with subsequent manual or automatic sorting. The precious metals from the printed circuit board fractions of the sorting process are recovered in copper mills or other metallurgical processes.

Lambda oxygen sensors are already partly removed and handed over to recycling companies due to their comparatively high value. As with the separation of vehicle electronics and the printed circuit boards they contain, recycling processes are already available here. The challenge therefore lies in the poor economic feasibility of separation and logistics.

The economical aspect could be improved if end-of-life vehicle dismantling facilities separate out easily removable components containing precious metals, and consolidate them with used parts that are unsaleable. Established pickup relationships with, for example, waste management logistics firms and treatment companies, should be developed for the pickup. For the latter, pickup logistics with consolidation of similar waste streams containing precious metals, e.g. from workshop or garage waste disposal, would be advantageous. Handouts for the dismantling facilities on the transfer of lean management approaches to dismantling processes can help to reduce the dismantling costs. Nonetheless, a market-driven approach with substantial volume effect does not appear to be realistic for this waste stream.

If a regulatory-driven approach were to be implemented, the following provisions mainly to be anchored in European law initially, would be feasible.

- Design specifications for the vehicle industry to install larger electronics components in a way that allows easy dismantling.

- Obligation to dismantle larger vehicle electronics components and to provide them to a recycling process, in which the printed circuit boards are separated and are passed on for precious metal recovery.

Other waste streams

Environmental catalytic converters containing precious metals: Environmental catalytic converters, which are used in small individual quantities, for example, in combined heat and power plants or in catalytic post-combustion, are mainly scrapped for steel or are placed in residual waste. A round table discussion with catalyst manufacturers and representatives of catalyst users could help to develop possibilities of providing improved information for users and for developing the take-back possibilities. As environmental catalytic converters are separated out anyway after replacement and are therefore basically easily accessible and recyclable, it should also be considered whether the introduction of a legal obligation for separate collection would be useful.

Waste streams containing cerium and lanthanum: Economic solutions, which would involve the development of time-consuming treatment processes requiring high investment costs, are not in sight due to the low value of these metals. Due to the high cerium content, the use of polishing sludge in ceramic glazing or in foundries could be possible. These are also hindered by economic considerations, however, the threshold is significantly lower here.

Phosphors containing rare-earth metals: The separation of phosphors from fluorescent lamps, CRT devices and LCD devices is standard practice. Processes are available for further treatment of rare-earth metal concentrates, but are currently not operated for cost reasons. If the processes were to be started up again, they could be supplied with the separated quantities available from existing processes. Consolidation concepts extending beyond this are not considered useful due to the small and decreasing quantity.

LCD layers containing indium: LCD devices are already removed and treated and the indium-rich glass fractions they contain are already separated out. However, there is a lack of opportunity to recover indium from the glass fraction. To this end, processes developed on a laboratory scale exist, but their implementation is not yet foreseeable. A legal regulation could be useful, which obligates the primary treatment facilities to collect the glass fraction containing indium obtained from the treatment of LCD devices separately and to add them to an indium recovery process. However, this requires the appropriate methods to be made available. To strengthen the willingness to invest, it would be helpful for suitable separation methods to be developed further on a pilot scale.

Tantalum capacitors: For recycling, tantalum-rich printed circuit boards must be sorted out by the primary treatment facility and enter operations for the disassembly and separation of tantalum capacitors. Processes are available for recovery of the tantalum from the capacitors. The operating companies of these processes already pay a remuneration for clean tantalum capacitors, depending on the current tantalum price. The printed circuit boards should be sorted by companies which operate the plants for separating out the tantalum capacitors and which have access to relatively easily accessible, large quantities of tantalum-rich printed circuit boards.

1.3 Interim storage until recycling technology is available

No adequate large-scale, industrial recycling capacities are currently available in Germany for the recovery of minor metals such as neodymium or indium from post-consumer waste. In addition to the development of suitable recycling technologies, an important requirement for investments in an industrial recycling plant is the generation of relevant quantities of waste containing minor metals. A feasible approach to creating the required volume streams and for bridging the time until the plant capacity is available is the interim storage of waste streams containing minor metals.

1.3.1 Storage design and requirements for the waste to be placed in storage

Before a conceptual storage design was developed, the requirements for the waste to be placed in storage were defined, in particular:

- Suitable degree of separation or treatment before being placed in storage (e.g. polishing sludge: dewatered)
- Minimum concentration of the minor metal to be recovered in future (e.g. phosphors: 1% rare-earth metals)
- Materials, components, impurities or pollutants to be removed before placing in storage (e.g. phosphors: glass, mercury)
- Weighing-up between pretreatment and concentration expense and storage expense (e.g. NdFeB magnets: with/without rotors)
- Condition for placing waste in storage (e.g. physical state, particle size, magnetisation, possible conditioning) (e.g. NdFeB magnets: demagnetised or shielded)
- Properties of the waste (composition, hazard potential, substance behaviour (e.g. leaching or emissions behaviour), maximum tolerable pollutant levels) (e.g. glass fractions containing indium: can contain toxic heavy metals)
- Description and consideration of the quality requirements for the input of the processes in development, where known (in general not known)

The minimum time required for the development of recycling processes was estimated for the various waste streams as follows:

- NdFeB magnets: in most cases more than 10 years.
- Polishing sludge containing cerium/lanthanum: 2 years.
- Separated glass fractions containing indium from the treatment of LCD: 5 years.
- Phosphors: 1-2 years.

- <u>NdFeB magnets:</u> Quantity and environmental relief potential in waste is currently dominated by IT products (hard drives, headphones and loudspeakers) as well as vehicle and industrial motors. By 2027, the total quantity of NdFeB magnets used in the various applications is expected to roughly triple. Regardless of their origin, magnets can be placed in storage under the same conditions, provided the waste is kept clearly and traceably separate according to sources, to enable a more targeted procedure for a future recycling company.

- <u>Phosphors:</u> The environmental relief potential is roughly one order of magnitude smaller than that of the other groups. Fluorescent lamps make the largest contribution. The quantities used can be assumed to reduce in future. Regardless of their origin, phosphors can be placed in storage under the same conditions, provided the waste is kept clearly and traceably separate according to sources, to enable a more targeted procedure for a future recycling company.

- <u>Waste streams containing cerium and lanthanum:</u> Largely unchanged future use quantities are assumed for all the waste streams examined. In view of the low material value of cerium and lanthanum as well as the foreseeable stable price situation, the development of a recycling process is not to be expected. Interim storage was only examined for polishing sludge, despite the small quantity, because due to the high target metal concentrations, the option of cost-efficient recycling exists here by using the recovered material in the ceramic industry and in foundries.

- <u>LCD layers containing indium:</u> Despite the rather small quantity, this waste stream has a comparably high environmental relief potential approximated by the carbon footprint main parameter. The quantities of indium used in this area are expected to double by 2035.

1.3.2 Basic legal conditions for interim storage

The interim storage of waste before their further disposal or recycling is subject to different waste, immission control and building regulation requirements. Apart from differentiating between the type and quantity of waste to be stored for an interim period, the duration of the interim storage also plays a decisive role.

The landfill legislation requirements for the interim storage of waste containing minor metals apply and specify in detail the immission control legislation obligations, as soon as waste destined for recycling is to be stored for a period of more than three years or waste to be disposed of is to be stored for a period of more than one year. In these cases, Sec. 23 para. 1 Landfill Ordinance ("Deponieverordnung "DepV") requires verification of subsequent proper disposal. If plants for the recycling of waste containing minor metals have not yet been completely designed or built, such verification of recycling can usually not be provided by the operator of the interim storage facility. For this reason, the legislator could create new legal exceptions in the Landfill Ordinance, which exempt waste containing minor metals from this duty to provide verification under the Landfill Ordinance. It is to be expected that such an amendment to the legal obligation in the Landfill Ordinance to provide verification will also affect the administrative practice for approving interim storage of waste under other regulatory instruments (immission control waste and building legislation).

A legal obligation to stockpile certain precious and minor metals would only be feasible if there was a change in the European and German raw materials strategy. In addition, the obligation to stockpile must comply with the principle of proportionality.

A long-term interim storage facility for minor metals can be operated by public bodies (e.g. financing via waste fees) or by private bodies or jointly. The legislator is able to stipulate obligations, e.g. financial obligations of manufacturers of products containing minor metals, in a separate legal provision. Sec. 25 KrWG (German Circular Economy Act) can be used as the legal basis for such a legislative ordinance.

Currently, there is no waste-stream specific hand-over or recovery obligations for waste containing minor metals. In particular, an obligation to store waste containing minor metals in interim storages cannot be deduced from the current separation requirements or recycling targets under the ElektroG or the End-of-Life Vehicle Ordinance. To create such an obligation, specific legal separation and recovery obligations for waste containing minor metals would have to be established (see in detail above at 1.2.2).

1.3.3 Assessment of the interim storage

The quantity of waste containing minor metals placed in storage will grow, at least until the recovery process to be developed has been put into service. After then, the timing of calls for stored quantities will depend on many factors, for example, the terms of sales, the quality of the material, the achievable revenue and availability from other sources. The long-term interim storage facility must be designed for a maximum storage quantity, however, which it will probably only reach for a relatively short period. The maximum storage capacity will be equal to several years' quantities. The investment costs for an autonomous storage facility with 1,000 m^2 storage area with additional auxiliary and traffic areas are estimated to be around one million euros. The additional operating costs incurred will probably be around € 100,000 annually. Another significant cost factor is the expenses for processing the material to be placed in storage, for example the dismantling (and demagnetisation) of the NdFeB magnets to be placed in storage.

1.4 Environmentally optimum recovery yield of precious and minor metals

Within the scope of this project, a tool was to be developed for roughly estimating environmentally optimal recovery yield, which can be applied with reasonable expense. The recovery yield (recovery rate) results from a sequence of yields via the process steps of the recycling chain, from the collection to the separation and treatment through to recovery. For each process step, different dependencies exist between the recovery yield and each indicator of environmental assessment, which can take the entire range from linear to highly exponential. In addition, the dependencies are also each coupled to defined processes, for example, the collection or treatment. Even if the derivation of such dependencies was theoretically possible with a great deal of data and calculation, a tool that works with such models would only feign the accuracy. In addition, due to the immense complexity, it would lack transparency and practical suitability.

Instead, a tool was therefore developed, which enables the estimation and rating of realistically achievable recovery yields. To this end, measures for increasing the recovery yield were identified and assessed qualitatively to semi-quantitatively with regard to the environmental efficacy and efficiency by means of benefit analysis in a spreadsheet tool. The underlying assessment method has seven steps:

1. Definition of the initial parameters for each partial quantity of a waste stream (e.g. target metal contents)
2. Breakdown of the status quo process into four process steps (collection, separation, treatment, recovery) as well as estimation of the current yield per process step
3. Measures for improvement
   a) Collection of possible measures (improvement approaches) for the process steps,
   b) Estimation of the yield improvement per process step
4. Qualitative/semi-quantitative assessment of the proposed measures with regard to 6 parameters, which are to be weighed relatively to each other: Environmental impacts due to the measure (global warming potential, toxicology), energy consumption (cumulative energy expenditure), effect on the yield of non-target materials and feasibility (realisation prospects, realisation expense)
5. Conversion of the qualitative assessment of each measure option into a numerical value as well as ranking of the proposed measures within the process steps
6. Offsetting the target metal yields of the proposed measures, which performed best within the process steps, against their primary metal values as well as the quantity of greenhouse gases, which would have been released for the primary production of the recovered target metals.
7. Overall assessment

The spreadsheet tool was applied to two examples.

Printed circuit boards from end-of-life vehicles:

In the status quo for this waste stream containing precious metals (assumption: 1,000 t printed circuit boards per year with an increasing trend and simultaneously decreasing precious metal content) it is assumed that the target metals considered - gold, silver, palladium and platinum – are currently completely lost during the recycling process for end-of-life vehicles. By implementing various measures/improvement approaches in the process steps with realistically estimated yield increases, a recovery yield (total yield) of 5.9 % can be achieved for the overall recycling process. This equals savings

- in greenhouse gas emissions of approx. 227,000 kg CO_2-equivalents,
- in fossil fuels and renewable energy sources equal to approx. 3.3 million MJ as well as
- in costs for purchasing the primary raw materials equal to € 566,000

Table 2: Assumed yields in the waste stream containing precious metals "Printed circuit boards from end-of-life vehicles"

Process step	Initial situation	After implementation of selected measures / improvement approaches	
		with realistically estimated yields	with very optimistically estimated yields
Collection	50 %	52 % (advertising, opening hours, etc.)	85 %
Preseparation	0 %	40 % (expansion of manual dismantling)	60 %
Treatment	0 %	30 % (impact mill and sorting step)	85 %
Recovery	95 %	95 % (copper mill)	96 %
TOTAL	0 %	5.9 %	41.6 %

With very optimistic assumptions regarding the increase in yields for the same measures/improvement approaches, the total recovery yield is almost 42 %.

<u>NdFeB magnets waste stream:</u>

In the initial situation, for this waste stream containing rare-earth metals (estimation: 402 t NdFeB magnetic material/a in 2020 with increasing trend) it is assumed that the target metals considered, dysprosium, neodymium and praseodymium, are currently completely lost during the recycling process chain. By implementing various measures /improvement approaches in the process steps of the recycling process with realistically estimated yield increases, a total recovery yield of 6.8 % can be achieved, see Table 3. This equals savings

- in greenhouse gas emissions of approx. 258,000 kg CO_2-equivalents,
- in fossil fuels and renewable energy sources equal to approx. 5.85 million MJ as well as
- in costs for purchasing the primary raw materials equal to € 675,000

Table 3: Assumed yields from the waste stream containing rare-earth metals "NdFeB magnets"

<table>
<tr><th rowspan="3">Process step</th><th colspan="3" rowspan="2">Initial situation</th><th colspan="6">After implementation of selected measures / improvement approaches</th></tr>
<tr><th colspan="3">with realistically estimated yields</th><th colspan="3">with very optimistically estimated yields</th></tr>
<tr><th>IM</th><th>IT</th><th>AF</th><th>IM</th><th>IT</th><th>EF</th><th>IM</th><th>IT</th><th>EF</th></tr>
<tr><td>Collection</td><td>30 %</td><td>50 %</td><td>50 %</td><td>30 %</td><td>65 %</td><td>52 %</td><td>60 %</td><td>70 %</td><td>85 %</td></tr>
<tr><td>Preseparation</td><td>0 %</td><td>0 %</td><td>0 %</td><td>50 %</td><td>20 %</td><td>30 %</td><td>70 %</td><td>85 %</td><td>80 %</td></tr>
<tr><td>Treatment</td><td>0 %</td><td>0 %</td><td>0 %</td><td>50 %</td><td>60 %</td><td>60 %</td><td>85 %</td><td>80 %</td><td>80 %</td></tr>
<tr><td>Recovery</td><td>0 %</td><td>0 %</td><td>0 %</td><td>85 %</td><td>85 %</td><td>85 %</td><td>90 %</td><td>90 %</td><td>90 %</td></tr>
<tr><td>TOTAL</td><td colspan="3">0 %</td><td colspan="3">6.8 %</td><td colspan="3">42.3 %</td></tr>
</table>

IM = magnets from industrial motors (60 t/a = 15 % of the total quantity considered)
IT = magnets from IT (275 t/a = 68 % of the total quantity considered)
AF = magnets from small e-motors from cars (67 t/a = 17 % of the total quantity considered)

With very optimistic assumptions regarding the increase in yields for the same measures/improvement approaches, the recovery yield is around 42 %.

1.5 Implementation of the measures for increasing recycling of precious and minor metals

The measures developed in the project were qualitatively assessed with a view to increase the recovered quantity of target metals, the degree of obligation, realisation prospects, realisation expense and effects on the recovery of other metals.

1.5.1 Magnetic materials containing rare-earth metals

The following measures could be useful for increasing the recycling of magnetic materials containing rare-earth metals, which are contained in waste electrical and electronic equipment and end-of-life vehicles:

- M 1: Labelling obligation

Labelling of motors (or other applications) e.g. on the type plate, which contain individual magnets larger than e.g. 20 g or a total quantity larger than e.g. 200 g. The labelling code indicates the magnet type (e.g. NdFeB), possibly extended with information of all rare-earth metals contained with fractions of more than 1 % by weight (e.g. NdPrDyFeB). It would need to be considered whether the labelling is also intended to enable differentiation between polymer-bonded and sinter magnets.

To be considered: The possibility of introducing mandatory labelling, e.g. via the ElektroG or the WEEE Directive or through European implementing measures based on the Ecodesign Directive or for motors through Regulation (EC) No. 640/2009 for implementation of Directive 2005/32/EC with regard to the specification of requirements for the Ecodesign of electric motors ("Motor Regulation"); and where useful extension to other products.

Note: Possible mandatory labelling for all permanent magnet types, so that increased use of other magnet types containing rare-earth metals would also be covered and evasive actions by substituting the magnet type would be prevented or are transparent.

Note: The labelling could be kept very simple for automatic sorting (e.g. NdFeB).

- M 2: Dismantling, recovery and information obligation

For motors or equipment with non-motor-dependent magnets, which are identifiable as containing NdFeB (e.g. in hard drives) or, as described under M 1, are labelled, dismantling obligation and obligation to feed the removed magnets into a recycling process, by which rare-earth metals from primary sources are substituted.

The obligations for waste electrical equipment could be anchored in the WEEE Directive (Annex VII) or in the German ElektroG (Annex 4) and for end-of-life vehicles in the EC End-of-Life Vehicle Directive (Annex I No. 4) or in the German End-of-Life Vehicle Ordinance (Altfahrzeugverordnung).

If requirements were defined there for the separation of components containing precious or minor metals, the manufacturers would have to provide appropriate dismantling instructions. To be considered: Expansion of existing initiatives for establishing a central, possibly internet-based dismantling instructions database (www.i4r-platform.eu).

Note: A dismantling obligation is only productive where a labelling obligation exists or, for example, the presence of NdFeB magnets is known due to the dismantling instructions. If necessary, wording such as "… are to be dismantled from equipment that is labelled accordingly or for which the presence of magnets containing NdFeB is generally known" could be added to the named regulatory provisions.

- M 3: Obligation to design for recycling

To be considered: Weighing up all aspects, does a requirement "magnets must be dismantlable non-destructively, by simple means" seem reasonable (possible conflicts with energy and material efficiency objectives)? If yes: Examine the possibilities for obligating the manufacturers or importers of the electric and electronic equipment or vehicles containing minor metals. If such a requirement is not reasonable, the dismantling obligation would also have to be limited, e.g. "dismantling, where technically possible, economically reasonable and taking into account the social consequences". Whether the cost is reasonable or not could be described in technical guidelines on the basis of criteria or component lists and these could be updated regularly.

- M 4: Recycling target

Introduction of a specific minor metal-based recovery target with reference to the quantity entering the recovery process: in any event, to be monitored with great effort, because to achieve this, not only the separated quantities and the quantities entering the recovery process, but also the yields of the recycling processes would have to be determined and collated (cf. therefore the possibility of a corresponding adjustment of the reporting obligations in the German legislation (ElektroG and AltfahrzeugV)).

- M 5: Creation of the possibility to set up long-term interim storage facilities

For NdFeB magnets or parts which, for example, contain at least 10% NdFeB magnets; possibility of setting up and maintaining privately operated long-term interim storage facilities, to which end amendments to the requirements for long-term storage in Sec. 23 DepV.

- M 6: Consolidation/pooling workshops

Workshops involving dismantling facilities , treatment companies , logistics and recycling companies providing services for dismantling facilities (including in other fields), see also section 1.5.8 of the summary.

- M 7: Promoting the development of transport and container systems for NdFeB magnet waste

Call for proposals for a research project with the participation of partners from practical areas; Step 1: Examining the suitability of systems, which are used to provide new magnets.

- M 8: Initiation of a collection and dismantling network for electric bicycles

Establishing of a voluntary cooperation between bicycle manufacturers, distributors and recyclers, e.g. through a workshop.

Furthermore, several general measures are worth considering, see Section 1.5.8 of the summary.

Assessment of the measures:

Compatibility with EU law: Measures M 1, 2, 3 and 4 would extend beyond the range of obligations currently defined in the WEEE Directive or the End-of-Life Vehicles Directive. Adjustment of the European regulatory instruments is therefore required and/or tightening the German regulations. A German over-implementation is possible in principle, due to the objectives of the WEEE Directive and the End-of-Life Vehicles Directive, the high level of protection for the environment provided for in Art. 114 para. 3 and 191 of the Treaty on the Functioning of the European Union ("TFEU") and the "reinforcement of protection" clause of Art. 193 TFEU. However, it would have to be ensured that these legislative measures do not have a negative effect on smooth functioning of the internal market or cause competitive distortions.

Additional reporting obligations within the scope of M 4 would also have to comply with implementing acts of the Commission for the specification of a uniform registration format and the frequency of reporting according to Art. 16 para. 3 WEEE Directive.

Within the scope of M 5 it would also have to be considered that the WEEE Directive explicitly does not recognise interim storage as recovery. The interim storage of components containing minor metals is also not recycling as defined in the End-of-Life Vehicles Directive. It would therefore require the European legislator to become active, if the definitions of recovery and recycling are to also include interim storage.

At European level, the provision of the measures according to M 1 and M3 as well as the dismantling instructions according to M2 would also be feasible in implementing measures according to the Ecodesign Directive 2009/125/EC.

Conclusion: Effective measures with a high degree of obligation are M2 in combination with M1, which can be additionally strengthened through M3 and/or M4. The implementation effort for M3 and M4 in particular, however, is fairly high. Measures with overall favourable assessments, which could be implemented at low expense, are M6 and M8. Both measures also have positive effects on the recovery of other metals. However, the degree of obligation is significantly lower here.

1.5.2 Printed circuit boards containing precious metals and lambda oxygen sensors from end-of-life vehicles

The following measures could be useful for increasing the recovery of precious metals from vehicle electronics:

- M 1: Design specifications for the vehicle industry

Obligation regarding dismantling-compatible installation (see e.g. VDI Guidelines 2243: Recycling-orientated product development) of larger electronic components in vehicles; to be anchored in the European End-of-Life Vehicles Directive and in the German End-of-Life Vehicle Ordinance, if applicable in the form of additional or added annexes; only productive in combination with an dismantling obligation for end-of-life vehicle dismantling facilities.

Limitation to relevant components, in order to avoid unreasonable expense; the separation recommendation of Groke et al. (Groke et al. 2017) could serve as an initial basis to identify the relevant components.

To be considered: It should first be investigated, to what extent trade-offs can occur with the weight reduction and material efficiency design objectives.

- M 2: Dismantling, recovery and information obligation

Obligation to dismantle larger vehicle electronics components and to feed them into a recycling process, in which the printed circuit boards are separated and are passed on for precious metal recovery; anchored in the End-of-Life Vehicles Directive, Annex I (Minimum technical requirements for treatment) No. 4 (Treatment operations to promote recycling) or in the Annex to the German End-of-Life Vehicle Ordinance.
If new requirements for the separation of components containing precious metals from end-of-life vehicles within the scope of the dismantling were to be specified by law, this would also mean that the manufacturers would have to provide appropriate added dismantling instructions for the dismantling facilities, which explain how these components containing precious metals can be dismantled.

- M 3: Improve the return of end-of-life vehicles

Increases the potential for the recovery of precious metals, not only in case of dismantling parts containing precious metals but also – with significantly poorer yields - on shredding non-dismantled components that are still in the end-of-life vehicles.

- M 4: Shredder optimisation

Promotion of projects for the improvement of precious metal yield (as well as the yield of other metals such as steel, copper and aluminium) from shredder fractions in case of components containing precious metals that are not dismantled; e.g. by calling for proposals for a research project with the participation of industrial partners.

- M 5: Consolidation/ pooling workshops

Within the scope of consolidation workshops, opportunities will be worked up for using and expanding existing networks, see also Figure 2. It could be useful to bring together dismantling facilities (and possibly other companies with similar waste from other industries) with their potential customers and logisticians to extend existing or to develop new networks. The objective is for appropriate agreements to be made in order to use already established pickup relationships and to set up new connections.

- Primary and general measures

Furthermore, several general, primary measures addressing end-of-life vehicle dismantling facilities can increase the efficiency of in-house and inter-company logistics, especially the development and introduction of a recycling enterprise resource planning system (RERP), possibly supported by a level detection system, as well as working up a "lean management" handout, see section 1.5.8of the summary.

Assessment of the measures:

Compatibility with EU law: Measures M 1 and 2 would extend beyond the range of obligations defined to date in the End-of-Life Vehicles Directive. Adjustment of the European regulatory instruments would therefore be required and/or tightening the German regulations. Such a German over- implementation is possible in principle due to the objectives of the End-of-Life Vehicles Directive, the high level of protection for the environment provided for in Art. 114 Para. 3 and 191 of the Treaty on the Functioning of the European Union ("TFEU") and the "reinforcement of protection" clause of Art. 193 TFEU. However, it would have to be ensured that these legislative measures do not have a negative effect on smooth functioning of the internal market or cause competitive distortions.

Conclusion: The only effective measure with high degree of obligation and overall favourable assessment is M2. However, the implementation expense here is fairly high. Measures M3, M4 and M5 have favourable assessments overall. These measures also have positive effects on the recovery of other metals, however, the degree of obligation here is rather small.

1.5.3 Environmental catalytic converters containing precious metals

The following measures could be useful for increasing the recovery of precious metals from environmental catalytic converters:

- M 1: Round-table discussion with catalyst manufacturers and users

Discussion of possibilities for better information of users (e.g. via QR code) and development of the take-back possibilities.

- M 2: Introduction of a legal obligation for separate collection

For example, within the scope of a legal regulation under the extended producer responsibility of the manufacturers and distributors of environmental catalytic converters (including obligations to keep separately and to take back), or, if the environmental catalytic converters are handled as commercial waste: Extension of the Commercial Wastes Ordinance ("Gewerbeabfallverordnung") with obligations of the end users of environmental catalytic converters to keep them separate.

Assessment of the measures:

Compatibility with EU law: For the national implementation of the measures under M 2 in legal regulations based on the German Circular Economy Act (KrWG) or in the Commercial Wastes Ordinance ("Gewerbeabfallverordnung"), the requirements of the Waste Framework Directive would have to be respected, in particular the requirements regarding waste hierarchy in Art. 4 and on extended producer responsibility in Art. 8 ff. Within this framework, no amendments to European law would be required.

Conclusion: M2 has good effectiveness with a high degree of obligation and a positive assessment overall. M1 has less effectiveness and commitment, but due to the low implementation expense it also has a positive assessment overall. There are no reliable figures on the precious metal content of this waste stream.

1.5.4 Waste streams containing cerium and lanthanum

Most waste streams considered are not suitable for the recovery of cerium and lanthanum because their concentrations and individual quantities are too small. Where quantities already exist in consolidated form (NiMH batteries, slags from the treatment of catalytic converters removed from cars), the ecological and economic value of the metals contained is too low to justify more complex activities for their recovery.

In addition, cerium and lanthanum are produced as low-value byproducts in the extraction of rare-earth metals from ore. The extent of mining activities is determined by the demand for metals of higher value that occur in less concentrated form in the ores. This leads to the availability of cerium and lanthanum at far lower and more stable prices than the other rare-earth metals. Supply bottlenecks are hardly to be expected here. The ecological backpack of cerium and lanthanum is also comparatively small. Recycling of these metals is therefore not advantageous, as long as this requires sophisticated recovery methods.

Cerium appears in polishing sludge in fairly high concentrations. The direct use of polishing sludge in ceramic glazes or foundries could be possible at comparatively low expense, provided suitable quality assurance measures are taken, and would substitute cerium and lanthanum from primary ores.

The following measure could be useful to increase the recycling of waste streams containing cerium and lanthanum from polishing sludge:

- M 1: Initiation of a workshop

Bringing together possible stakeholders of the process chains for the use of polishing sludges in ceramic glazes or foundries.

Conclusion: The only measure option has a positive overall assessment at low implementation expense.

1.5.5 Phosphors containing rare-earth metals

Methods are available for the treatment of phosphors to produce rare-earth metal concentrates, but are currently not operated for cost reasons. If the processes were to be started up again, the already separated quantities from existing treatment processes for lamps and equipment could be fed to these plants. Measures extending beyond this are not useful, due to the low and also declining quantity. No options are named for measures concerning these waste streams.

1.5.6 Separated LCD layers containing indium

The following measures could be effective in improving the recovery of indium from separated LCD layers:

- M 1: Research project on the treatment of glass fractions containing indium

Initiation of a funded project on the implementation of the treatment of glass fractions containing indium produced by the treatment of LCD devices on a pilot scale, with material flow and cost-effectiveness balances worked up for the production scale.

- M 2: Creation of the possibility to set up long-term interim storage facilities

For separated LCD layers containing indium; possibility to set up and operate privately operated long-term interim storage facilities, which can be facilitated by amendments to the requirements for long-term storage in Sec. 23 DepV.

- M 3: Obligation to separately collect and recycle glass fractions containing indium

Obligation of the primary treatment facility to collect the glass fraction from the treatment of LCD devices separately and to feed them into a process for indium recovery; this could be anchored in the WEEE Directive (Annex VII) or in the German Electrical and Electronic Equipment Act (ElektroG) (Annex 4).

Assessment of the measures:

Compatibility with EU law: Measure M 3 would extend beyond the range of obligations defined to date in the WEEE Directive. Therefore, an adjustment of the WEEE Directive would be required and/or an amendment of the ElektroG. Such an over-implementation in the German ElektroG is possible in principle, due to the objectives of the WEEE Directive, the high level of protection for the environment provided for in Art. 114 Para. 3 and 191 of the Treaty on the Functioning of the European Union ("TFEU") and the "reinforcement of protection" clause of Art. 193 TFEU. However, it would have to be ensured that these legislative measures do not have a negative effect on smooth functioning of the internal market or cause competitive distortions.

Within the scope of M 2 it would also have to be considered that the WEEE Directive explicitly does not recognise interim storage as recovery. It would therefore require the European legislator to become active, if the definition of recovery is to also include interim storage. Furthermore, by changing the requirements for the long-term storage of waste in Sec. 23 DepV (German Landfill Ordinance), the German legislator could simplify the operation of such an interim storage facility.

Conclusion: The only measure with high effectiveness and commitment is M 3. This measure has a positive assessment overall. M1 also has a favourable assessment overall. However, the degree of obligation is rather low here.

1.5.7 Separated tantalum capacitors

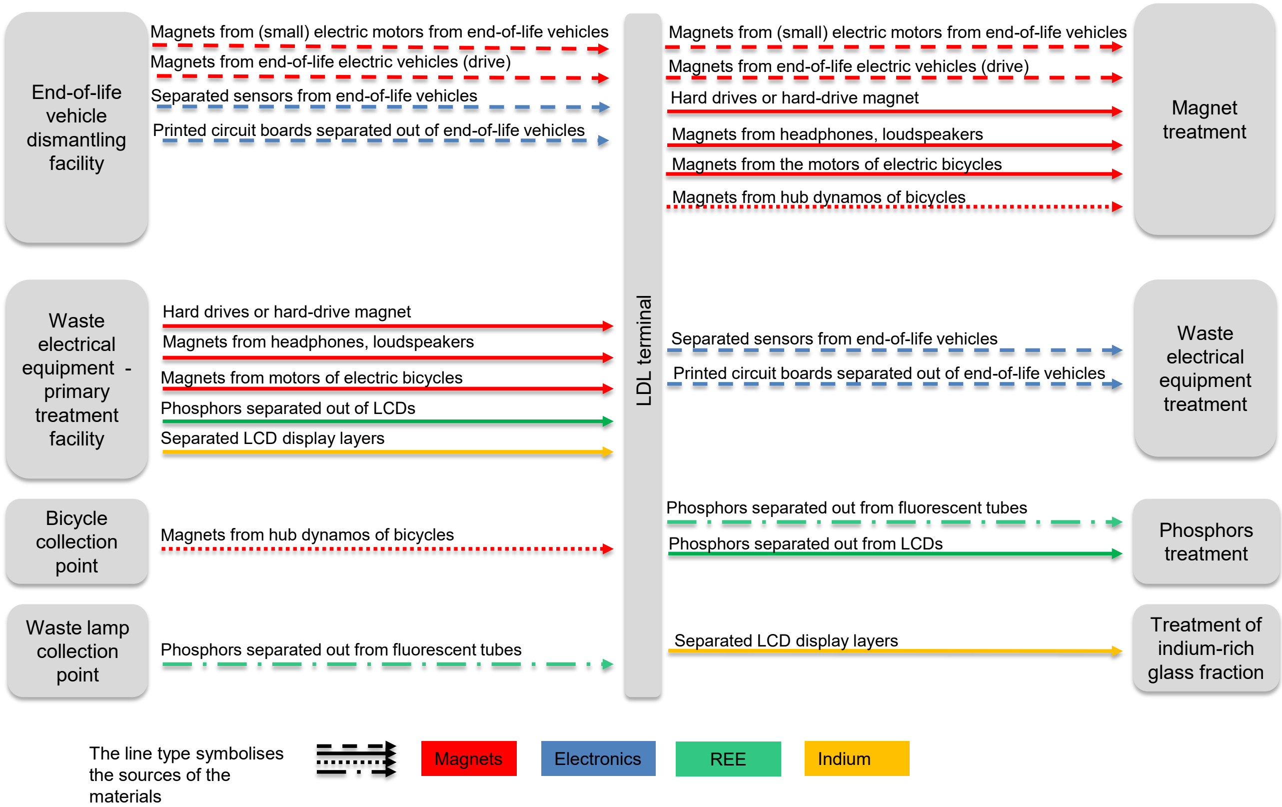
In principle, consolidation would be possible by involving all primary treatment facilities. However, to do this, they would have to relinquish high-quality printed circuit boards, which they already sell profitably. Tantalum's share of the overall value is very small; it therefore offers hardly any motivation for such action. In addition, separating out printed circuit boards with relevant tantalum content would require significant sorting expense, which could not be reasonably reimbursed by potential purchasers of the printed circuit boards. The printed circuit boards should therefore be sorted out by companies which if appropriate operate their own plant for separating out the tantalum capacitors. Such plants can offer prospects of large quantities of tantalum-rich printed circuit boards that are relatively easy to access and, once they are in operation, they can attract further quantities from interesting market segments with an eye toward the target metals. No measures are named for this waste stream.

1.5.8 Primary general measures for logistics and consolidation/pooling

In addition to the specific options described above for individual waste streams, further action options exist on a general level to increase the efficiency of in-house and inter-company logistics, which target overall waste stream and material flow management in the companies, and not only the specific waste streams containing precious and minor metals. Nevertheless, they can have positive effects on the recovery of the target metals from waste. These measures are located in the process steps dismantling and recovery:

- promoting the development of a recycling enterprise resource planning system (RERP), in-house and/or inter-company,
- working up a "lean management" handout,
- the development and distribution of level detection systems, for example, to support an RERP, as well as
- cross-material flow consolidation, see Figure 2, which aims to improve capacity utilisation of the transport movements in logistics chains. If a terminal is interposed, the consolidation is largely independent of the contents of the transported objects. The consolidation potential results from the spatial proximity of the pickup addresses or the target destinations downstream of the terminal. This can be supported, for example, by consolidation workshops.

Figure 2: Consolidation potential of selected material flows.

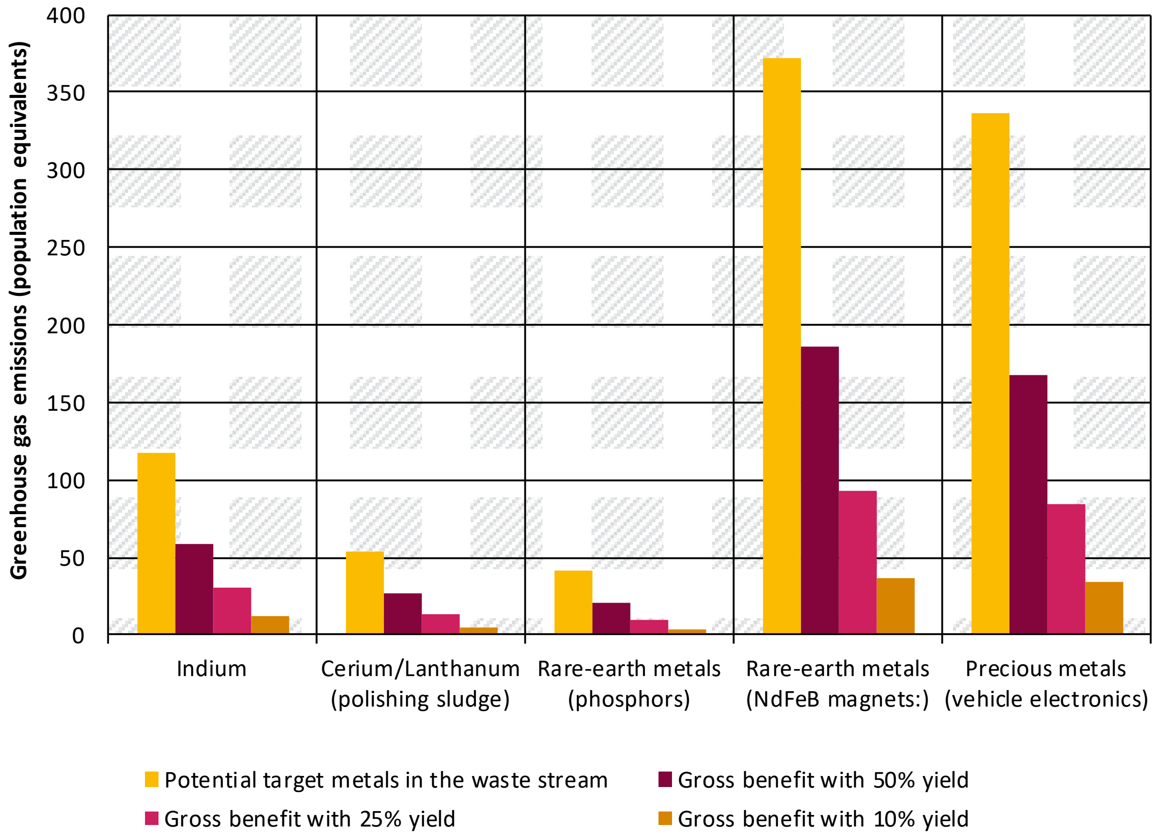


In addition, there are options for measures that take effect at a higher level and that can develop effects that are self-regulating and largely independent of dynamic technical and economic changes. Examples of this include: Increasing return quantities by reinforcing enforcement, preferential tax benefits for recycling processes, tax advantages for the use of recyclate or material tax or CO_2 tax on materials from primary raw materials in relation to their carbon footprint. The analysis and assessment of these measures is not the subject of this study.

1.5.9 Reasonableness of measures

The cost of realising and implementing measures to increase recycling should be proportionate to the expected ecological benefits. Therefore, the environmental relief potential achieved by recycling the target metals in the waste stream considered, which results from avoiding the primary production, has been estimated using the indicative parameter of greenhouse gas emissions (Figure 3).

Figure 3: Gross environmental relief potential of the target metals in the waste streams considered by substituting primary production; represented on the basis of the indicative parameter of greenhouse gas emissions (figures in population equivalents); population equivalents of carbon footprint in Germany: 11.4 t CO_2eq/a (Source: Umweltbundesamt 2018); Carbon footprint of target metals: Dy, Tb: PLoS (2014); all others: ecoinvent (2017).



The possible ecological benefit of measures for improving recycling is limited to the share of metals effectively recovered from this potential. Due to incomplete collection and losses along the process chain, the actual yield to be expected can be significantly lower. The greenhouse gas emissions caused by the recycling processes must then be deducted from this gross benefit.

Even in the case of NdFeB magnets and if quantities increase significantly in the future, the potential will probably increase to a few thousand population equivalents. The effectively expected benefit with regard to greenhouse gas emissions, however, will hardly exceed a few hundred population equivalents in Germany even in the next years due to exports in the form of used equipment, losses along the recovery chain and greenhouse gas emissions from the recovery. At least from the view of climate protection, the implementation of elaborate legislative measures therefore seems hardly appropriate.

In addition to climate protection, other aspects are relevant regarding the question of the appropriateness or proportionality of (legal) measures to increase the recovery of precious and minor metals, for example:

- Other environmental impacts from the primary extraction of the metals, these include, among other things, radioactive radiation emissions during the extraction of rare-earth metals or mercury emissions from small-scale (artisanal) mining of gold.
- The security of supply, particularly with critical raw materials.
  The list of critical raw materials for the EU 2017 (European Commission 2017) includes,

among other things, the precious and minor metals indium, tantalum, platinum group metals as well as light rare earth metals and heavy rare earth metals considered in the project. In the Circular Economy package (European Commission 2015, page 16), the EU Commission encourages the member states to promote the recycling of critical raw materials. The increasing attention of the European waste management on the critical raw materials is also made clear in that since May 2018 they have been explicitly addressed in the Waste Framework Directive, among other things, in order to reduce the dependency of the Union on resource imports (European Union 2018).

- The securing of raw materials, especially for future climate protection technologies that will become increasingly relevant in the future, such as photovoltaic systems, wind turbines and electromobility.
- In the medium or long-term, increased quantities of many of the precious and minor metals considered can be expected in the waste streams.

However, the assessment of these aspects must also take into consideration the expected substantial losses along the recovery chain of most of the waste streams considered.

Nevertheless, further activities for improving or realising the recovery of the target metals from the waste streams considered are purposeful and desirable. Thus, in certain constellations, for example, direct access of an equipment manufacturer or recovery company to suitable waste quantities, the separation of target metals can be ecologically and possibly even economically advantageous - insofar as purchasers for the produced material are available in precisely these constellations. Distinct price peaks in case of high demand can also be good preconditions for the development of limited recovery activities, because purchasers temporarily appear on international markets. And finally, individual players succeed every now and then in developing creative solutions for partial quantities of waste streams. In addition, in several of the named fields it is possible that individual players will set up comprehensive solutions on their own initiative, if this is in order to support other economically more promising activities.

Targeted and limited activities by the state can be helpful, if they support the own initiative of the stakeholders. For example, players can be brought together at consolidation workshops or round table discussions. For the participants, this can be interesting, especially if they aim to achieve basic improvements, with which the possible recovery of the metals considered here is only one of many feasible positive effects. This is the case, for example, in the development of recycling enterprise resource planning systems or the development of lean management handouts especially for small and medium enterprises.

Legislative measures, which take effect on a higher level, can improve the preconditions for the player's own initiatives. For example, measures to improve compliant collection of end-of-life products such as end-of-life vehicles or waste electrical equipment lead to larger quantities of precious or minor metals accessible to interested players, but in particular to larger quantities of bulk metals. The creation of a possibility for long-term interim storage of suitable separated components or materials by recycling companies also contributes to the expansion of their room for manoeuvre. This can help with the development of solutions, and not only for the metals considered here.

2 Consolidation (Pooling) of waste streams containing precious and minor metals

2.1 Collection logistics concepts and design of information flows

The business logistics is a scientific discipline, which does not follow a uniform paradigm. The management of flow systems is an understanding of logistics that is currently taking hold, which offers empirically verifiable, successful guidelines on strategic planning as well as tactical decisions and the operative control of logistics systems. In general, as a business discipline, logistics is orientated on efficiency increasing mechanisms, which were successfully established in industrialisation. Logistics sees value-adding processes or recycling processes as a network of connected players/companies, who implement the overall process together. The networks are represented in node and link models. Nodes represent, for example, warehouses, stores and companies and links represent the connecting supply relationships. Such a model visualises the network and provides information about the number and properties of the nodes, if applicable their location relative to each other and about the interconnection of the nodes (links) as well as their properties. Logistics networks are multi-level. The levels focused on here are the physical level of the goods and the informational level for control of the physical goods level. Improvements of logistics processes can take place on both levels, in which case they each have a reciprocal influence on each other. The financial level was also examined. This provides incentive and motivation for entrepreneurial action.

The challenges in pickup recycling logistics differ in several aspects from those of distribution logistics in providing value-adding chains. The challenges in recycling chains were therefore assembled generically on the named levels and the respective approaches to solutions were described in detail. shows an overview of the challenges and solutions, structured according to steps in the recycling chain and network level.

Table 4: Challenges and solution approaches along a generic recycling chain

	Collection point	Sorting and dismantling	Recovery
Physical level	Challenge: Problem of the first mile Time and material consolidation Organisation of container systems Fit-for-use handling in collection points **Solution:** Route planning for time (and material) consolidation as well as volume consolidation Shortening of the process stopping times	Challenge: Positioning of sorting and dismantling in the recycling chain Optimisation of manual processes to reduce unit labour costs **Solution:** Compilation and provision of dismantling information in the chain	Challenge: (Intralogistics) Storage close to production/treatment locations Storage of containers Logistical processing of co-products **Solution:** Allocation of supply and demand
Informational level	Challenge: Control of collection processes Triggering of pickups Quantity plannability Degrees of freedom for planning processes Reduction of stopping costs/stopping times **Solution:** Automation or partial automation of level indication Quantity plannability degrees of freedom for planning processes Digital spot market platform for pickup Notification to reduce stopping costs	Challenge: Identification of recoverables Information on accessibility for dismantling **Solution:** Auto-ID system for the identification of recoverables in components Open information platforms for information on the accessibility of the components Provision of validated dismantling instructions on (open) platforms	Challenge: (Control of the intralogistics) Planning of distribution of the products by allocating supply and demand **Solution:** Spot markets vs. cooperations
Financial level / Motivation/ Incentive	Challenge: Legal obligations Economic attractiveness Interaction of both aspects **Solution:** Award at market prices to logistics service providers, who are able to increase potential consolidation effects	Challenge: Increase in economic attractiveness by structuring the learning curve **Solution:** Targeted use of the experience curve	Challenge: Revenue optimisation vs. customer loyalty Logistic expenditures for by-products **Solution:** (Spot markets vs. cooperations)
	Coordination tasks of logistics as a cross-disciplinary function		

The “first mile” of waste management logistics, in the same way as the “last mile” of distribution logistics, is particularly challenging. The “last mile” in logistics describes the transport to the customer’s “front door” and is characterised by a large number of widespread delivery points with small quantities per delivery. The “last mile” share of the total delivery costs is correspondingly high. In the same way, in waste management logistics, the “first mile” of the waste, from the potentially numerous collection points / dismantling facilities to the treatment plant, often with small quantities, is accompanied by large challenges.

If logistics is understood to be the management of flow systems, a significant efficiency gain lies in cross-company or cross-step coordination of process chains. Therefore, a model was also considered in which companies acting as system operators coordinate the entire logistics process, across all the individual steps. Several solution approaches indicated in the steps can be integrated into such a concept.

An essential pillar of logistics management is the availability of information. No, or very few, recycling chains currently exist for waste containing precious and minor metals considered here. Accordingly, hardly any historical values are available. One proposal is therefore to support the establishment of a software-based system which, on setting up a recycling chain, collects and stores data on logistics processes (especially movement and quantity data), in order to enable data-based iterative process improvements. These can take place in-house, but also across companies and steps in the coordination of whole process chains.

RERP as an information base for cross-chain logistics management

A recycling enterprise management system can be used to collect and manage a large quantity of operational information on the incoming and outgoing objects (waste and recoverables (recyclable and recoverable materials)) as well as on customers, suppliers, etc. in a structured way. The information can also be used to fulfil legal information obligations. In general, the benefits of a recycling enterprise management system result from the totality of its options. The management and utilisation of information on waste streams containing precious and minor metals will be a partial aspect of such an overall operational decision.

The platform should also make it possible to link manufacturer information on the composition of objects (material and in the assembly) to the assumed objects. To realise this, an online interface must be created, via which the manufacturers can provide the information on their products. The basic waste stream-specific requirements for manufacturer information must be defined within the scope of the requirements analysis. For example, batch numbers can be used to connect the collected products to this information. It may also be necessary to use an alternative numbering system. Other sources for such information (free platforms) should also be made accessible. Other requirements are to be worked up from practice in a requirements analysis.

Auto ID systems (such as RFID) can clearly identify components and can be linked via the RERP to information on the installation location and dismantling information. Provision of the necessary information by manufacturers is extremely critical due to trade secrets. Accordingly, it is unlikely that manufacturers would store this information to be freely accessible. An alternative solution would be open information platforms, on which manufacturers can add product information, but also other interested parties can, for example, report on their experience of the accessibility of components from the dismantling process. Such collective knowledge could be used in a similar way to a wiki platform. It is decisive that a critical mass of (non-professional) experts, who provide their empirical values and information such as their experiences, is reached. In general, the level of motivation for supporting recycling processes can be assessed as positive. Whether the critical mass of interested parties would be reached can only be answered after a real “go live” of such a platform.

In the same way as other open source projects, the backup, processing and validation of accessibility and dismantling information could constitute a business model. For example, SUSE LINUX GmbH distributes the open-source product Linux professional and offers additional services such as support and tested updates.

A specific proposed action for all recoverable flows is the establishment of a database for improved control of the recoverable flows. It is helpful to support the development of software which, like an enterprise management system (working title: Recycling enterprise resource planning system: RERP) provides the possibility of registering incoming disposed of objects in information terms.[1]

In the first step, the benefit of the RERP relates to improved control of the workflow organisation within the stages (in-house) of a recycling chain. The RERP provides the opportunity, in particular, to collect movement and quantity data. Based on these data, processes can be evaluated subsequently and planned and controlled more efficiently in an iterative process. The system is therefore suitable for all recycling chains that are not yet adequately digitalised. Once such systems have been established, it is then possible to couple them and to organise cross-company or cross-chain processes more efficiently on a data basis.

Level recording for optimisation of route planning

Level recording offers service providers the opportunity to optimise the organisation and capacity utilisation of tours in their transport networks.

Different options exist for level recording, which also depend on the measured goods and recoverables. In addition, different degrees of automation are also conceivable. The following variants appear to be basically plausible for the containers for waste containing precious and minor metals and could be promoted:

- Recording by barcode scanning, whereby the barcode represents a specific level (50%, 75%, 95%; …) and the employee does not have to enter a number.
- Recording via a mobile application and a mobile device (smartphone, tablet, etc.) using a ready-made menu (50%, 75%, 95%; …).
- Use of sensors (recording via weight, brightness in the container, pressure on container walls, etc.).

All variations have in common that the information is recorded locally, directly at the collection site and is reported over WLAN. Collection centres require appropriate infrastructure for this. That is to say, all collection centres should be completely covered with WLAN and receive a powerful internet access. Activities for this coincide with the expansion of broadband, which can be supplemented to include the coverage of collection centres, often located on the edge of town, with (public) WLAN.

As collection centres represent the starting points for different material flows, there is a risk of individual solutions being created and different solutions being used in the collection centres. Therefore, a standardised solution for data collection should be promoted, to ensure its use. This particularly applies if manual processes are at least partly necessary in the workflow, i.e. recording using an application OR barcode as well as the reporting of levels to a website or integration of the level recording into the RERP mentioned above.

The specific recommended action is to couple the RERP work to the level measurement work. The persons affected are the same stakeholders, who ultimately have to assess which measurement type is useful and implementable in their respective area. In the second step, the purchasers should be asked about their information needs and this should then be incorporated into the applications. Not only the question of realising level measurements but also the design of an RERP should, however, not only be analysed and evaluated with regard to the waste containing precious and minor metals relevant here, but rather as a possible contribution to the general further development of practical workflows in the companies. Level measurement is particularly relevant for systems in which service providers or a company's own fleet drive to specific destinations with collection containers on regularly scheduled routes. Especially large potential is to be expected in recycling chains that have stochastic quantities and work with a relatively large number of collection containers. The unplannability of stochastic volumes can be compensated for by level measurement.

[1] While similar approaches already exist, for example, in the recycling of end-of-life vehicles, such systems still have to be developed and established for other waste streams. However, the constituents focussed on in ILESA are not explicitly covered in existing solutions.

Workshops for realising cross-material stream consolidation effects

The consolidation of material flows enables streamlining of the logistic processes through better capacity utilisation of the means of transport and possibly the choice of larger and generally more cost effective means of transport. Consolidation options should also be considered, which are not primarily focused on the target raw materials.

Two basic consolidation options exist:

- Pure logistical consolidation of different material / waste streams from a point of generation
- and the consolidation of waste with joint target metals or with a common treatment method.

In addition, it is possible to combine the consolidation solutions; however, this requires an additional sorting process.

Consolidation is aimed at utilising the capacity of the logistics chains, especially the transport movements. Therefore, the logistical consolidation is largely independent of the constituents of the transported objects. The consolidation potential results from the spatial proximity of the pick-up address and delivery address. Consolidation is conceivable, which picks up several objects from a source or consolidation that delivers the objects to one target destination. Both consolidation options can be realised if the transported objects are sorted between them (cf. Figure 4).

Consolidation is only advisable where, due to the nature of the object, unutilised transport capacities can be expected, at least theoretically, and other objects can also be transported without additional trips (i.e. in spatial proximity). Consolidation is particularly attractive economically, if existing transport network capacities are utilised better. Therefore, workshops with firms are proposed, which already maintain appropriate transport networks, i.e. drive to collection centres or treatment points.

Workshops organised and held by the German Environment Agency can be suitable, for example, in consultation with the respective industry associations. The underlying assumption is that redundancies can be uncovered on “overlaying” the existing logistical networks. Transport movements with smaller quantities could possibly also be incorporated. The consolidation in a transport is not raw material dependent, but instead depends on the availability of load space and the compatibility of the container systems in a transport.

More precise details cannot be decided until the workshops. The extent to which waste streams can be transported together with regard to legal or technical aspects must then be checked in detail.

The targeted benefits are:

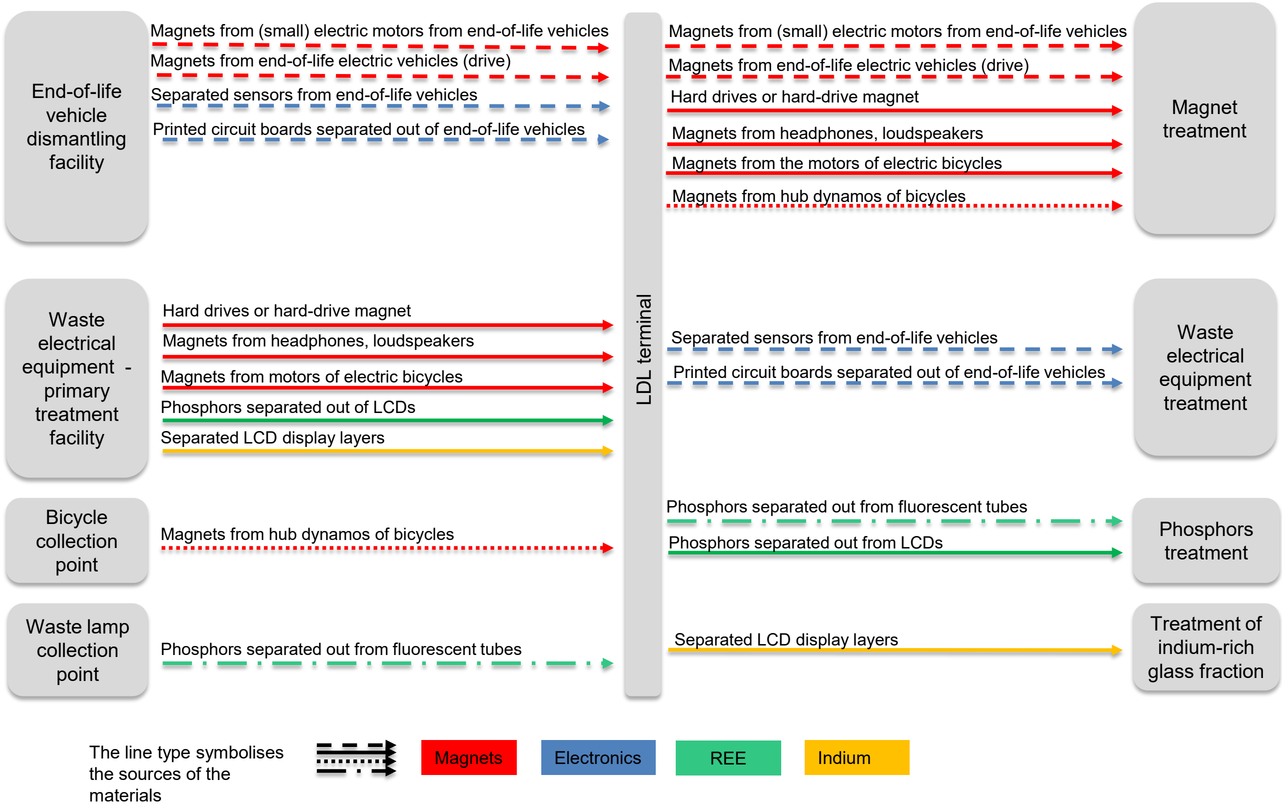
- uncovering synergies between already established transport networks,
- uncovering potential for use of existing transport networks for new recoverable movements (vehicle payload) and
- uncovering opportunities for cooperation in the logistics of present day systems.

A further workshop constellation could be to bring together collection centres (from the same or even from different industries) with their potential purchasers and logistics specialists for the development of new networks. This can always be helpful if the stakeholders concerned are not yet in the business relationships.

In addition, the alternatives should be pursued, to use already established networks, for example, for the recovery of automotive catalytic converters, at least for the collection of the packages with different materials occurring in the end-of-life vehicle recovery facilities. Alternatively, other logistics networks could also be used, which already drive regularly to end-of-life vehicle recovery facilities. This is enabled by involving the processors of automotive catalytic converters or alternative collection route operators in the discussions. As their logistics service providers drive to the relevant collection centres anyway, it is conceivable that an additional quantity of packages is helpful, even if small, to improve the service provider’s capacity utilisation and to share the costs for the logistics.

Figure 4 shows the consolidation options to be dealt with in the workshops. The material flows have been selected according to useful consolidation possibilities. For example, the magnets of wind turbines are not suitable for consolidation due to the pick-up locations. Under the proposed concept, one (or several) transport companies collect all waste streams of a collection centre, in order to rearrange them into new material streams in regional transfer centres. The treatment companies can then be sent larger, consolidated quantities and therefore be supplied more efficiently.

Figure 4: Consolidation potential of selected material flows.



Here it is critical for the purchasers to be basically interested in general cooperation and coordination of the logistic provider's service. The logistics service providers must then separate the combined material flows in a depot and re-sort them according to their further recovery. For example, vehicle electronics, vehicle sensors or small electric motors from cars are packed in packages, are collected by a service provider and are forwarded to a waste electric equipment treatment facility on the one hand and a magnet treatment facility on the other hand. As an efficient distribution network has been set up via online trading, this could be accomplished relatively inexpensively for small-volume waste streams with an appropriate framework agreement. This requires that the packages can be added to the distribution process without major handling effort and that the permissibility of the transport movements under waste legislation is ensured. The latter must be checked as soon as useful consolidations and the type of transfer are identified.

Efficiency increase through learning curve in the dismantling process

Manual dismantling activities are viewed as being critical cost drivers. In recent decades, lean management methods have established themselves to reduce manual work and are particularly promising. The objective of lean management is to eliminate inefficiencies (in lean management terminology: waste) in value creation processes. In lean management, waste is each activity that does not create any value. The types of waste defined in lean management are:

- Transporting: Longer transport of materials does not add any value.
- Inventory: Inventory that is not needed ties up resources, space and capital.
- Motion: Unnecessary movements of the workers, in order to fetch materials and tools or to pick up the same workpiece several times do not add value.

- Waiting: Waiting times in production, waiting for replenishment of raw material or due to a machine failure.
- Overproduction: Manufacturing products without customer orders only causes increased stocks without certainty that the end products will be purchased.
- Wrong technology/ processes: Long work operations (low-quality raw material, poor tools) and laborious or complex processes waste time and resources.
- Rejects/rework: Production of defective parts or rework on finished products is also waste under lean management.

Lean management approaches should be used in a targeted way to reduce dismantling effort and costs. The expected cost reduction makes carrying out the recovery more attractive economically. As an action, a lean management manual should be developed with the companies involved and the dismantling employees concerned , which transfers the different methods to the specific basic conditions and describes them in an application related way.

2.2 Information needs and transfer

The information needs are very different depending on the stakeholders, substance and material flows considered, product or component types and the respective industries. The main complexity differences mostly lie in the ability to identify and access the parts to be dismantled. Collection and consolidation as well as information on the actual recovery are mostly less complex.

Types of information and organisation of the flow of information in the disposal stakeholder chain

The information required in the individual steps of the disposal and disposal logistics can only partly be acquired or added by the respective stakeholders themselves. Frequently, information is required about the components of interest, their position in the product and the possibility of acquiring these components or parts of them quickly and reliably.

Here an information network whose nodes and edges have to be filled by the different stakeholders is suitable.

Using the example of vehicle parts, for example, the supplier will only have limited information about the substances and materials used in the parts. This information ("what's in it?") can only be requested from the manufacturers of the components, who in turn supply individual parts to the suppliers. These part manufacturers are not necessarily in the automotive industry. For example, a manufacturer of magnets, who supplies magnets to manufacturers of electric motors.

To answer the question "what's in it"? and other questions in the disposal chain reliably, a complex network of information is already required, which has to be filled with data from the production process. Different information is produced:

Material-related data: The information about the substances and materials used is most likely to be available at the start of the production and supply process. However, it can by no means be assumed that in each production process it is known, which fractions of the materials used are actually still present or available in the produced part, as this is not necessarily the focus of quality controls.

Part/subproduct-related information: Information produced at the start of the production chain could be collated in this first production step in the same way as parts lists, so that the material composition of the parts is available for the subsequent production processes.

Product-related information: The actual producer or distributor of the product, which is to be recovered later, has the information about which parts and components are used to produce the product within the scope of the production process.

In particular, the producer can supply information on the location and possibly on the accessibility of the parts considered. They will at least be able to provide repair and maintenance information for complex products such as a motor vehicle, which indicates the location of the components and the possibility of removing and replacing them.

Dismantling and demounting information: The repair instructions provided by the producer are often not very helpful for efficient dismantling, as destructive methods can also be used in the dismantling to acquire recoverables and therefore the work can be quicker (cf. Groke et al. 2017, p. 130 and 141). Access to concealed installed units can be substantially easier, if other units have been removed beforehand. This knowledge of proper and efficient dismantling and demounting (e.g. of components containing precious and minor metals), for example, of an end-of-life vehicle, on the one hand represents the in-house know-how of the dismantling facility, but on the other hand is very highly dependent on which possible recovery options are used by the company. The location and types of components, which contain electric motors or printed circuit boards, differ depending on the vehicle type and features, but are relatively simple for an experienced employee to identify, especially if they are visible. It is far more difficult to estimate which constituents, such as the precious and minor metals considered and what quantities of these are actually contained in the individual components (e.g. controllers, small motors). Especially if these materials have been substituted or their content reduced, this information about the specific component concerned is lacking.

Collection-related information: Within the scope of the collection and consolidation, information is initially required if certain mixing bans exist for different collection fractions. Before a specific transport operation, information about the collection locations, containers and levels are required or helpful; during and after a specific transport knowledge about the whereabouts is required (quantity, quality, delivery address, possible batch/container identifiers).

Recovery-related information: The information about the available recovery processes and their basic conditions is fundamental. Costs and revenues, quantities and qualities as well as the acceptance conditions must be known, so that recovery alternatives can be selected. Where individual recovery processes take place on different stakeholders' premises (e.g. removal of plastic fractions, demagnetisation, crushing, chemical treatment), the basic conditions must be known for each of these intermediate steps.

Industry-related information: Industries play a central role in the provision of information and targeted exchange of recommended actions. For the planning of disposal routes and the acquisition of quantities, it is essential for disposal companies to know in which industries components with specific materials are used. Take-back systems are frequently implemented successfully within the scope of extended producer responsibility, if they are designed as an industry solution. Positive effects, to be expected due to cross-industry consolidation of batches with similar material quantities, also initially require knowledge of the individual industries in which products arise with specific quantities and waste types.

Individual firms and corporations often have reservations about reporting data directly to official bodies or other market participants, to which they do not have a direct business relationship. Here they frequently fear handing over trade secrets. The collection and transfer of information and data by associations or independent service providers can ensure a minimum of data and information anonymisation. Also, industry organisations often find it easier to approach known contacts and to win them over to willingness to generate data than previously unknown third parties or official bodies.

Additional data: Where identification systems exist, the corresponding keys such as serial numbers, component numbers, part numbers, EAN codes (European article numbers), etc. should also be taken into consideration. These data are available from the supplier and can make it easier to identify the parts later, as in most cases these numbers can be found on the components.

The substances and materials used during the different preproduction or production steps can most easily be named during these steps and their quantities stated or estimated. In the other production and assembly steps, parts lists are available in most cases, in which reference is made to delivered parts and units with the respective identifiers (part numbers). In addition to the information of a parts list, it must also be possible to record if the material compositions of the parts have changed due to substitution or reduction of certain fractions.

The information on the location and installation of the parts and units is only available for highly automated production processes, and then mostly not in generally available information systems, but integrated in production and robot controls.

2.3 Legal aspects of the separation and labelling of waste streams containing precious and minor metals

Based on the current status of research and development, it is to be expected that in the medium-term, large-scale treatment and recovery processes will be available in Germany for certain types of precious and minor metal waste and corresponding plant capacities will then be created. Such waste occurs in particular in the recovery of end-of-life vehicles and waste electronic and electrical equipment. Against this background, it was examined which provisions of the Electrical and Electronic Equipment Act (Elektro- und Elektronikgerätegesetz - "**ElektroG**", German transposition of the WEEE Directive), the German End-of-Life Vehicle Ordinance (Altfahrzeug-Verordnung "**AltfahrzeugV**", German transposition of the End-of-Life Vehicles Directive) and which general regulations under waste or product law, which influence the recovery and recycling of the waste containing precious and minor metals, in particular from waste electrical and electronic equipment ("**WEEE**") and end-of-life vehicles, and how these regulations can be changed, in order to improve the reclamation and recovery of waste containing precious and minor metals.

2.3.1 Provisions for waste containing precious and minor metals, which is covered by the ElektroG

2.3.1.1 Removal obligations for components containing precious and minor metals from WEEE

Until now, as part of the primary treatment of WEEE, certain components must be removed, which can contain precious and minor metals (cf. for example the obligation to remove printed circuit boards). On the other hand, there is no general obligation to separate all components containing precious or minor metals from WEEE, with the aim of recovering the precious or minor metals.

At the European level and – subject to compatibility with EU law – at the German level, the legislator could stipulate an obligation to separate out components containing precious and minor metals from WEEE as part of the primary treatment. In Germany, this would be in an ordinance according to Sec. 24 No. 2 Var. 1 ElektroG or in an amendment to Annex 4 ElektroG. As a result, the material flows could already be separated in this early stage. Limiting the removal and recovery obligations to a specific magnet type (NdFeB) is also conceivable.

2.3.1.2 Addition of recycling / recovery targets for components containing precious and minor metal from WEEE

At present, as far as we are aware, the recycling and recovery targets of the ElektroG required to date are achieved, even without recycling or recovery of the components containing precious and minor metals from WEEE. Therefore, the targets set to date do not create (sufficient) incentive to recover these components containing precious and minor metals components. In addition to the already mentioned removal obligations as part of the primary treatment, the legislator could therefore legally define specific recycling / recovery obligations or recycling/ recovery targets for precious and minor metals. It is possible, and can be necessary, to stipulate recycling / recovery targets for individual material flows only, for example, magnet type (NdFeB), insofar as this can be justified under best available technique or environmental protection considerations, including taking into account the overall effects and the efficiency of resource use.

It is advisable to anchor accompanying notification and reporting obligations in law, to ensure corresponding monitoring of the compliance with the (extended) recovery targets.

2.3.1.3 Consideration of temporarily stored components in the recovery rate

Until now, the interim storage of components containing precious and minor metals cannot be classified as part of the recovery and cannot be included in the recovery rates according to the ElektroG. This results from the clear wording and legislative history of Sec. 22 ElektroG and Art. 11 para. 2 subpara. 2 WEEE Directive.

As components containing precious and minor metals are currently not recovered separately, and despite this, as far as we are aware, the required recycling/ recovery targets are achieved in practice, it is possible that even extraction and interim storage of individual components containing precious and minor metals would not prevent the recycling/ recovery target from being achieved in practice. If reaching the recycling or recovery target should become problematic in practice due to the interim storage, an amendment of the ElektroG would be one option so that interim storage, at least of the components containing precious and minor metals, could be classified as (possibly preliminary) recycling/ recovery by way of an exception provided that the actual future recycling is assured.

However, such an amendment to the national law is currently not in accordance with the requirements of the WEEE Directive, which explicitly does not recognise interim storage as recovery. If a change in the recovery definition is the objective, this would have also have to be done at the European level and not only the national legislation level.

2.3.1.4 Labelling obligations for electrical and electronic equipment

Labelling the electrical and electronic equipment to the effect that it indicates that it contains components containing precious and minor metals, is not provided for yet, either in the WEEE Directive or in the ElektroG.

A statutory amendment of the labelling obligations for components containing precious and minor metals for the purpose of informing the end user is in principle possible. However, doubt exists regarding its proportionality, insofar as separate treatment and recovery obligations only are to be introduced, and not separate collection channels for WEEE containing precious and minor metals and the location of the components containing precious and minor metals are otherwise known to the primary treatment facilities.

2.3.1.5 Dismantling information for WEEE

Provided that removal obligations for components containing precious and minor metals from WEEE are extended by law, this also leads to the extension of the legally required dismantling information of the manufacturers of electrical and electronic equipment, without requiring further legal specification. There is therefore currently no legal obligation to transfer dismantling information for WEEE to a central, possibly internet based, computing system. At present, the law only requires that the information is provided in the form of manuals or in electronic form (CD ROM, online services). At present, there is apparently no central database for WEEE such as the one for end-of-life vehicles. However, there are already efforts to establish such a database (cf. the new online platform for recyclers of WEEE of the WEEE forum as well as the manufacturer associations, Digitaleurope and Ceced (www.i4r-platform.eu)).

Such a central database can be set up by voluntary or a self-commitment cooperation of the manufacturers. Moreover, a statutory obligation to set up a central database for WEEE is possible. In the event of statutory organisation of a mandatory dismantling information database and enhanced statutory information obligations for manufacturers, adequate protection of the company and trade secrets of the manufacturers as well as compliance with the general data protection and competition law requirements would also have to be ensured.

2.3.2 Provisions for waste containing precious and minor metals, which are covered by the AltfahrzeugV

2.3.2.1 Dismantling of components containing precious and minor metals from end-of-life vehicles

Before transferring the remaining chassis to a shredder facility or another facility for further treatment of certain components, operators of dismantling facilities must remove certain components, substances and materials and primarily direct them into reuse or material recovery processes. These include, for example catalytic converters, balance weights, aluminium rims and metal components containing copper, aluminium and magnesium, if the relevant metals are not separated out during or after shredding.

At European level, extended obligations to extract components containing precious and minor metals components could be added to the End-of-Life Vehicle Directive, which would then have to be implemented accordingly in German law. The German legislator can also act independently of the European legislator and – subject to compatibility with European law – can stipulate an obligation to extract the components containing precious and minor metals in the Annex to the AltfahrzeugV.

2.3.2.2 Recovery rate

Sec. 5 AltfahrzeugV, which implements Art. 7 para. 2 End-of-Life Vehicle Directive, already contains recovery rates for end-of-life vehicles. If an additional recovery rate for removed components containing precious and minor metals is to be stipulated by law, this can be done through an addition to these existing recovery rates. Such separate recovery rates for precious and minor metals – according to the explanations on the ElektroG – should be accompanied by corresponding notification and documentation obligations for the dismantling facilities.

As the interim storage of components containing precious and minor metals components does not yet amount to a reprocessing of the waste materials for their original purpose and is thus not material recovery as defined in the German AltfahrzeugV or recycling as defined in the End-of-Life Vehicle Directive – according to the explanations to the German ElektroG and the WEEE Directive – a change in the definition at European level, and not only at German level, is required if interim storage is to be deemed recycling or material recovery in the future.

2.3.2.3 Labelling

If components containing precious and minor metals are to be labelled in the future, this could be stipulated in the End-of-Life Vehicle Directive itself, in implementing regulations of the European Commission or in the AltfahrzeugV.

2.3.2.4 Dismantling instructions

To implement the statutory obligation to issue dismantling information, the automotive industry created a computer-based information system IDIS (*International Dismantling Information System*), which provides the required information on the dismantling of certain components for many brands and models in more than 20 languages.

If new requirements for the extraction of components containing precious and minor metals from end-of-life vehicles within the scope of the dismantling were specified by law at European or German level, this would also mean that the manufacturers would have to provide appropriate added dismantling instructions for the dismantling facilities, which explain how these components containing precious and minor metals can be removed.

2.3.3 General waste legislation provisions for waste containing precious and minor metals

As long as no specific statutory requirements apply, as, for example, for the dismantling of individual large tools or large plants, which do not fall within the scope of the German ElektroG or AltfahrzeugV, the general obligations to keep separate and recover under waste law apply initially. For these waste streams, a statutory addition to the German Commercial Waste Ordinance (Gewerbeabfallverordnung - "**GewAbfV"**) is conceivable. If the waste that occurs when dismantling large tools/large plants does not always clearly fall within the scope of the GewAbfV (for which there are several indications), these waste streams could also be included in the scope of the Commercial Waste Ordinance through a corresponding addition to the scope of the GewAbfV.

Specific statutory requirements are currently not yet evident for (i) the suppliers of motors containing NdFeB magnets (as long as these are not themselves electrical and electronic equipment) or of other components containing NdFeB magnets, (ii) manufacturers of fixed large industrial tools or fixed large plants containing NdFeB magnets or (iii) manufacturers of NdFeB magnets themselves. It is conceivable in principle, to address these constellations in a separate ordinance – or depending on the scope – in a separate law which specifies the extended producer responsibility under waste law. However, such provisions would have to comply with the principle of proportionality. In addition, dovetailing with the existing obligations of the German ElektroG and AltfahrzeugV would be required in particular, where the NdFeB magnets are (also) contained in WEEE or end-of-life vehicles and are to be exempted from the recovery obligations scheme of the manufacturers under these regimes.

2.3.4 Labelling and dismantling instruction provisions in implementing measures under the EU Ecodesign Directive 2009/125/EC

Further, in principle, it would be conceivable to stipulate requirements for the labelling of certain product groups containing precious or minor metals at European level, in implementing measures under the EU Ecodesign Directive 2009/125/EC. Labelling obligations and obligations to provide dismantling information in implementing measures based on the EU Ecodesign Directive 2009/125/EC would not only have to satisfy all requirements of the EU Ecodesign Directive 2009/125/EC, in particular Art. 15 EU Ecodesign Directive 2009/125/EC, but must also comply with the principle of proportionality. In particular, on issuing any implementing measures, it must be assessed carefully which waste legislation obligations already apply, in particular under the WEEE Directive, in order to determine which additional waste requirements under eco-design legislation are required.

2.4 Recovery processes, consolidation and information concepts

Technical recycling processes for waste streams containing precious and minor metals have been and are developed in different research projects, some very differentiated. However, an overall picture is rarely obtained from this, as these process chains are at best conceived with sufficient specificity for individual waste streams and larger parts of the required overall chain, from the primary treatment stage through to the production of (future) marketable products. In addition, the projects are partly based on very different basic conditions. This is also not surprising.

However, without defined recovery paths and business models, the development of consolidation and logistics concepts is only possible to a limited extent. For example, before defining logistics chains, the logistics-critical aspects of the overall technical process must be clarified (e.g. what is to be delivered by whom to whom and in what form). These in turn depend on the business models of the stakeholders.

In the final analysis, however, it would not be at all useful, from the overarching perspective of this project, to anticipate reality with a closed model, which must be negotiated and created by the stakeholders involved, not only in the case of the primarily market-driven approaches but also in case of primarily regulatory-driven approaches.

A preview of possible embodiments of this occurrence in the form of an in-depth scenario analysis is basically possible, but was not planned within the scope of this project. From today's point of view, it is only possible to outline principle scenarios, which could offer potential starting points for the realisation of consolidation of the waste containing precious and minor metals examined.

Approaches with broader consolidation effectiveness could be driven above all by two factors:

- One or several recovery facilities make the financial outlay and consolidate such large quantities of waste streams that economic recycling is made possible for them. In doing so, they create a contractual and cooperation structure with other companies.
- Statutory obligation forces stakeholders to implement consolidation and recovery systems.

Here it can be assumed that these factors do not have an ideal-typical effect. For example, companies already exist, who concern themselves with the collection and recovery of the examined waste streams and which will probably remain active in this field in case of a statutory requirement. On the other hand, it is also definitely possible to support the existing or planned activities, for example, of recovery facilities, through targeted funding or even through more cautious statutory measures.

Which of these approaches or, if applicable, which combinations of several approaches could be productive for the waste streams to be analysed and whether such a consolidation effect appears realistic and appropriate at all, is analysed in the following for selected waste streams.

In all the logistical assessments of material flows presented, for reasons of simplification, in the first approach

A) 100% of the collected quantity is assumed, i.e. all recoverables placed on the market also return to the system along the route provided and

B) 100% of the primary metal pricesfor the target metals (average metal prices over a period of five years).

Both assumptions mark upper values that are not achievable realistically, but which are used as an indicative framework, to estimate whether economic solutions can be conceivable. In the case of the quantities, the actually collected fractions without rigid legal requirements is generally far below 100%. The actually achievable revenue from the recovery mostly lies significantly below the primary metal prices values. Above all, however, if there is a lack of statutory regulation with which, in case of an economically viable solution, the target metal values contained in the waste finance the entire recovery chain, i.e. not only for example the costs of the dismantling facility. In case of a solution driven by legal requirements, that is not economic per se, the financing of the recovery chain must be clarified. And finally, in each recovery chain, target metal quantities are lost, i.e. 100% yields are never achieved.

For all recommended actions, close cooperation is recommended with stakeholders, who are already involved in the relevant value stream. The objective must be to giv already active recycling companies the opportunity to process further material flows and to recover even more recoverables. That is to say that already active companies must be disburdened and supported more, and legal activities should be targeted at acquiring new stakeholders for the recycling.

3 The consolidation of NdFeB magnets and vehicle electronics

3.1 The consolidation of separated magnetic materials and vehicle electronics containing rare earth metals

3.1.1 Waste streams and actual processes

Numerous studies have been undertaken on the feasibility and potential of the recovery of rare earth metals from permanent magnets. An overview of the current research status is given by Yang Y. et al. (Yang Y. et al. 2016; p. 122-149), Elwert et al. (Elwert et al. 2017) and by Binnemans et al. (Binnemans et al. 2013; p. 1–22).

The information on the rare-earth metal content of the magnetic materials given in this report are to be viewed as an approximation, as there can be substantial spread in composition within the application groups. The quantities and values given do not represent the actually available potential, because a large part of these quantities does not occur as waste in Germany, and in most cases also not in Europe, because they are contained in equipment exported as used equipment. A further substantial share is lost through improper disposal. Corresponding figures are not available for all waste streams.

Today, 58 % of the total potential quantity and half the total potential value of the NdFeB magnets are attributed to IT. The three largest sources, namely IT, industrial motors and small e-motors from cars together account for more than 80% of the potential quantity and value. A rapid growth in quantities of NdFeB magnets is expected for electric bicycles, cars and air-conditioning systems.

The fate of IT magnets

In the EU and Germany, the collection of WEEE is specified in the WEEE Directive and ElektroG, respectively. In most primary treatment facilities, hard drives and loudspeakers are crushed mechanically together with other equipment parts and are then sorted. Magnetic particles adhere to steel parts during sorting, and are thus sorted into the steel fraction and are subsequently smelted. The rare-earth metals are completely lost.

The fate of magnets from industrial motors (Buchert et al 2014; p. 14 ff, p. 33 and p. 34.)

Damaged motors as well as machines and plants containing motors, are given to repair companies, which either return them repaired or sell them to disposal companies, and there they are generally shredded and are sorted automatically without separation of magnetic materials.

Magnets are rarely replaced when defective motors are repaired. Therefore, these magnets generally do not arise until the end of the motor's life, which is given as 12 - 20 years for industrial motors with rising trend (Almeida et al 2012, as cited in Buchert et al. 2014; p. 24). As motors with NdFeB magnets have only been used increasingly for the past approx. 10 years, larger waste quantities are not expected until the future.

In general, identification of motors containing NdFeB by the disposal companies is currently not ensured.

Table 5 shows the potential quantities and value of waste NdFeB magnets in Germany for the year 2020 from different areas of use as well as the typical compositions of the magnets.

Table 5: Potential quantities and value of NdFeB magnets in waste in the year 2020 from different areas of use as well as the typical compositions of the magnets

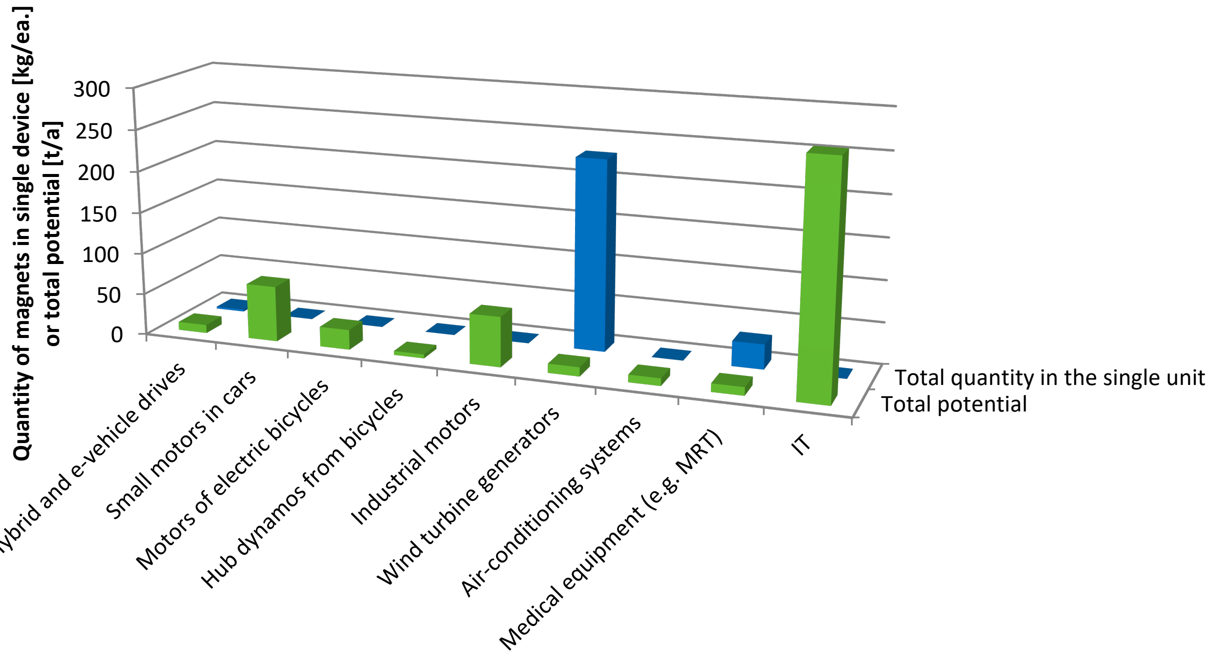
Scope			Total quantity of the waste stream (Magnetic material) 2020				Trend
	Composition (%)	primary metal prices [1] of REM in magnetic material	Germany[2]		Germany & neighbouring states (in brackets: EU total)[3]		
		€/kg	t	k€ (max.)	t	k€ (max.)	
IT (hard drives, headphones, loudspeakers)	Nd: 26-31 Pr: 0- 5, Dy: 0	15 - 22	275 [4]	6,100	700 (1,380)	15,210 (30,000)	falling
Industrial motors	Nd: 20 Pr: 0, Dy: 10	43	60	2,580	153 (302)	6,567 (13,130)	rising
Electric bicycles: Motors	Nd: 25 Pr: 4, Dy: 2	24	24	580	61 (120)	1,470 (2,900)	rising sharply
Wind turbines	Nd: 29 Pr: 0- 4, Dy: 2-6	17-35	11	385	28 (56)	978 (1,927)	rising
Cars (hybrid and electric vehicle drives)	Nd: 20 Dy: 10	43	10	430	25 (50)	1,096 (2,193)	rising sharply
Cars (small e-motors)	Nd: 28 Pr: 1, Dy: 1	19	67	1,273	168 (335)	3,182 (6,277)	rising sharply
Air-conditioning systems	Nd: 20–28 Pr: 0-2, Dy: 0-10	12-21	9	180	22 (43)	456 (900)	rising sharply
Hub dynamos	Nd: 21 Pr: 0, Dy: 9	41	5	200	12 (24)	497 (980)	rising
MRT	Nd: 20-29 Pr: 1- 5, Dy: 1-5	15-33	10	330	25 (50)	838 (1,658)	constant
Total			**471**	**12,058**	**1,194 (2,360)**	**30,294 (59,965)**	

[1] REM = rare-earth metals; Nd: 51 €/kg; Pr: 122 €/kg; Dy 331 €/kg (Source: USGS 2017)
[2] Sources: Values for Germany are based on data from Sander et al. (Sander et al. 2017; p. 35; as well as Sander et al. 2012, p. 58), except cars (hybrid and electric vehicle drives) [Assumption: 4,000 vehicles with approx. 2.4 kg magnetic material per vehicle (Zepf 2015, p. 469)] and cars (small e-motors) [Assumption: 134 g magnetic material in magnets per vehicle (Basis: Groke et al. 2017; p. 87 and 89: approx. 30-50g rare earth metals per non-current vehicle) with 500,000 vehicles; only collected vehicles here, Potential higher, but not known];
[3] Estimate for neighbouring countries and EU state estimated via GDP; neighbouring states: the larger neighbouring states are taken into consideration: France, Belgium, the Netherlands, Austria, Denmark, the Czech Republic and Poland.

[4] derived from the mean value of the totals of all Nd content quantified in Sander et al. 2012, p. 58 in equipment of collection group 3 (information and telecommunication equipment, until November 2018)

As Figure 5 shows, the quantity of magnet per single unit in the waste streams with the largest occurrence (small e-motors in cars, industrial motors and IT) is very small, while the waste streams with a large quantity of magnets per single unit (wind turbine generators, air-conditioning equipment and medical equipment) currently have only a small total potential.

Figure 5: Total quantity in the single unit in kg/each versus total potential of magnet material in waste streams in Germany in the year 2020 in t/a

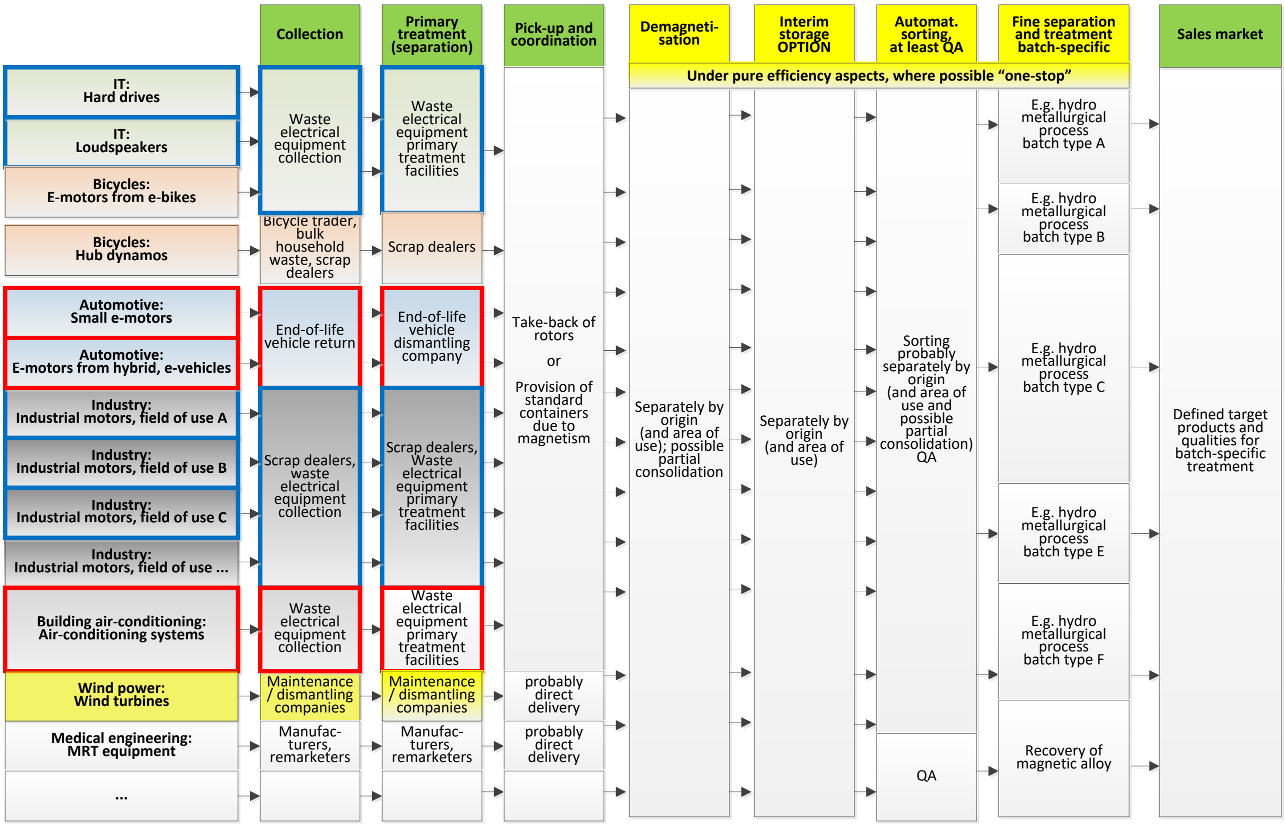


3.1.2 Technical target recovery chains

Process chain concept

Figure 6 shows a possible rough process chain concept for the consolidation and processing of NdFeB magnets from different sources.

Figure 6: Rough process chain concept for the consolidation and treatment of NdFeB magnets from different sources; blue frames: currently dominant waste streams in quantity terms; red frames: rapidly growing volume streams



A basic differentiation must be made between two types of consolidation: Consolidation in the picking up and consolidation in the treatment / preparation and processing.

At which points in the process chain the material is to be consolidated, i.e. mixed, for the treatment and processing of partial quantities, cannot be defined globally in advance. Among other things, this depends on

- Size and uniformity of the partial quantities: For large and uniform quantities, separate processing and thus keeping separate until late process steps, is often economically more efficient. Small and rather inferior partial quantities tend to be merged earlier and processed together.
- Type and quantity of foreign substances contained: E.g. mixing large, clean material streams with less clean streams must be avoided.
- The type of treatment process planned for a material: Each method has different process input requirements
- The quality assurance requirements: The higher the quality assurance requirements, the more important the traceability of material flows through to the material source. Large and high-quality individual quantities run through different quality assurance processes to small and rather inferior quantities.

- The customer markets' product quality requirements for the respective end products and the level of expected remuneration: These factors in turn influence for which waste streams it is economically advantageous to keep them separate

Joint processing of all partial streams in one process to form a rare-earth metal concentrate is conceivable in principle; however, it has substantial disadvantages:

- The achievable added value is rather low.
- There is no possibility of producing different types of product (e.g. magnet alloys, demand-based uniform concentrates).
- The technical process in each step and for the entire mass stream must at the same time be oriented to all expected material properties, contaminations, etc.
- The value of large individual magnets with uniform composition is reduced by mixing them with other material.

It is therefore highly likely that it can be assumed that – even within the system shown in Figure 6 - process variations occur.

Consolidation level and level of motivation

In which form should consolidation take place (consolidation level)

Depending on the design of the recovery path, the consolidation should either take place in the form of separated NdFeB magnets and/or where possible in the form of separated rotors containing NdFeB magnets.

The separation depth, to which magnets from individual primary treatment facilities are passed on advantageously, however, does not only depend on the recovery path itself, but also on the primary treatment facilities, on the quantities generated there, on the technical equipment, on the level of knowledge of the employees and on the current market prices for scrap, copper and magnetic material. A successful recovery system will have to have a certain flexibility with respect to these basic conditions.

At which points in the process chain should consolidation take place

Figure 6 shows possible consolidation points in the recovery process chain. Consolidation is advisable in principle in the companies that remove magnets or components containing magnets, such as rotors from different areas of use. Depending on their origin, the magnets have different compositions and impurities. They can be transported to the treatment together, provided they are quantities that are accepted there. But they should be packaged separately, so that they can be input into different quality control and treatment processes. The merger of such partial quantities must be left to the treatment facility or treatment facilities themselves, because control of the processes will have to be adjusted depending on the market situation, technical equipment and the requirements of the treatment facility's customers.

The market players and their level of motivation

The question arises as to which market players could most likely be expected to take the initiative to set up a consolidation and recovery solution.

- **Magnet manufacturers** mainly produce outside of Europe. They are hardly expected to set up collection and recovery solutions in Germany and Europe. In addition, waste management is not part of their core business.
- **Manufacturers of products containing magnets** mostly do not purchase raw materials, but instead purchase finished motors or magnets. Interest in setting up a collection and recovery

solution could develop in individual industries or large manufacturers, who manufacture products with large magnets and growing potential quantities and service them themselves or sell them through leasing concepts. However, cross-industry activities are hardly to be expected here.

- **Dismantling facilities** have access to only limited quantities. Metallurgical recovery processes are not part of their core business. Isolated activities, such as the removal and selling on of larger magnets, are conceivable. However, a comprehensive and overarching initiative from this group appears hardly realistic.
- **Logistics companies** generally have experience neither in the area of primary treatment nor in the operation of complex recycling processes. Their core business would not be a significant factor for success. They are therefore also hardly potential initiators.
- **Dealers / agents** already purchase NdFeB magnets for export depending on the market situation. But it is not to be expected that they will set up a more comprehensive recovery system. They have neither the required key competencies nor would their core business be a significant factor for success.
- **Operators of complex hydrometallurgical or metallurgical recycling processes, with their** experience in operating such processes with appropriate specialisation, appear to be the most likely to be motivated and suitable for setting up a corresponding field of business. Nevertheless, a substantial success risk also exists for them.

The role allocation shown is idealised. For example, there are recovery facilities, which also operate as traders or logistics companies. Overarching collaborations between different stakeholders are also possible; however, they would also have to be initiated and promoted by someone.

3.1.3 Scenario for a possible market-driven collection and consolidation concept

Market-driven setting up of comprehensive activities for the collection and recovery of waste containing NdFeB magnets could, for example, occur according to the following scenario: The market as well as, at the same time, the process technology, logistics and cooperation structure are set up successively and actively, driven by a recovery facility, which treats magnets to produce marketable products.

Rather cautious state/regulatory measures, which do not substantially intervene in the market, could have a supporting effect

- Targeted business development in the form of financial grants for the setup and test operation of the pilot plant for the extraction of alloys for reuse, the hydrometallurgical pilot plant, the demagnetisation plant and the sorting facility
- Creation of the possibility of setting up a long-term interim storage facility by the company
- Labelling obligation for magnets (see below)
- Potential removal and recovery obligation (see below)

The prerequisites for the market-driven realisation of a recovery solution, despite all difficulties, do not appear poor. Before such activities are intensified, however, the return of units containing NdFeB magnets must increase substantially. Only when larger quantities are within range in time, is it to be expected for companies to commit themselves beyond research projects and tests.

3.1.4 Regulatory measures

The following measures could be useful for increasing the recycling of magnetic materials containing rare-earth metals, which are contained in waste electrical and electronic equipment and end-of-life vehicles:

- M 1: Labelling obligation

Labelling of motors (or other applications) e.g. on the type plate, which contain individual magnets larger than e.g. 20 g or a total quantity larger than e.g. 200 g. The labelling code indicates the magnet type (e.g. NdFeB), possibly extended with information of all rare-earth metals contained with fractions of more than 1 % by weight (e.g. NdPrDyFeB). It would need to be considered whether the labelling is also intended to enable differentiation between polymer-bonded and sinter magnets.

To be considered: The possibility of introducing mandatory labelling, e.g. via the ElektroG or the WEEE Directive or through European implementing measures based on the Ecodesign Directive or for motors through Regulation (EC) No. 640/2009 for implementation of Directive 2005/32/EC with regard to the specification of requirements for the Ecodesign of electric motors ("Motor Regulation"); and where useful extension to other products.

Note: Possible mandatory labelling for all permanent magnet types, so that increased use of other magnet types containing rare-earth metals would also be covered and evasive actions by substituting the magnet type would be prevented or are transparent.

Note: The labelling could be kept very simple for automatic sorting (e.g. NdFeB).

- M 2: Dismantling, recovery and information obligation

For motors or equipment with non-motor-dependent magnets, which are identifiable as containing NdFeB (e.g. in hard drives) or, as described under M 1, are labelled, dismantling obligation and obligation to feed the removed magnets into a recycling process, by which rare-earth metals from primary sources are substituted.

The obligations for waste electrical equipment could be anchored in the WEEE Directive (Annex VII) or in the German ElektroG (Annex 4) and for end-of-life vehicles in the EC End-of-Life Vehicle Directive (Annex I No. 4) or in the German End-of-Life Vehicle Ordinance (Altfahrzeugverordnung).

If requirements were defined there for the separation of components containing precious or minor metals, the manufacturers would have to provide appropriate dismantling instructions. To be considered: Expansion of existing initiatives for establishing a central, possibly internet-based dismantling instructions database (www.i4r-platform.eu).

Note: A dismantling obligation is only productive where a labelling obligation exists or, for example, the presence of NdFeB magnets is known due to the dismantling instructions. If necessary, wording such as "… are to be dismantled from equipment that is labelled accordingly or for which the presence of magnets containing NdFeB is generally known" could be added to the named regulatory provisions.

- M 3: Obligation to design for recycling

To be considered: Weighing up all aspects, does a requirement "magnets must be dismantlable non-destructively, by simple means" seem reasonable (possible conflicts with energy and material efficiency objectives)? If yes: Examine the possibilities for obligating the manufacturers or importers of the electric and electronic equipment or vehicles containing minor metals. If such a requirement is not reasonable, the dismantling obligation would also have to be limited, e.g. "dismantling, where technically possible, economically reasonable and taking into account the social consequences". Whether the cost is reasonable or not could be described in technical guidelines on the basis of criteria or component lists and these could be updated regularly.

- M 4: Recycling target

Introduction of a specific minor metal-based recovery target with reference to the quantity entering the recovery process: in any event, to be monitored with great effort, because to achieve this, not only the separated quantities and the quantities entering the recovery process, but also the yields of the recycling processes would have to be determined and collated (cf. therefore the possibility of a corresponding adjustment of the reporting obligations in the German legislation (ElektroG and Altfahr-zeugV)).

- M 5: Creation of the possibility to set up long-term interim storage facilities

For NdFeB magnets or parts which, for example, contain at least 10% NdFeB magnets; possibility of setting up and maintaining privately operated long-term interim storage facilities, to which end amendments to the requirements for long-term storage in Sec. 23 DepV.

- M 6: Consolidation/pooling workshops

Workshops involving dismantling facilities, treatment companies , logistics and recycling companies providing services for dismantling facilities (including in other fields), see also section 1.5.8 of the summary.

- M 7: Promoting the development of transport and container systems for NdFeB magnet waste

Call for proposals for a research project with the participation of partners from practical areas; Step 1: Examining the suitability of systems, which are used to provide new magnets.

- M 8: Initiation of a collection and dismantling network for electric bicycles

Establishing of a voluntary cooperation between bicycle manufacturers, distributors and recyclers, e.g. through a workshop.

Assessment of the measures:

Compatibility with EU law: Measures M 1, 2, 3 and 4 would extend beyond the range of obligations currently defined in the WEEE Directive or the End-of-Life Vehicles Directive. Adjustment of the European regulatory instruments is therefore required and/or tightening the German regulations. A German over-implementation is possible in principle, due to the objectives of the WEEE Directive and the End-of-Life Vehicles Directive, the high level of protection for the environment provided for in Art. 114 para. 3 and 191 of the Treaty on the Functioning of the European Union ("TFEU") and the "reinforcement of protection" clause of Art. 193 TFEU. However, it would have to be ensured that these legislative measures do not have a negative effect on smooth functioning of the internal market or cause competitive distortions.

Additional reporting obligations within the scope of M 4 would also have to comply with implementing acts of the Commission for the specification of a uniform registration format and the frequency of reporting according to Art. 16 para. 3 WEEE Directive.

Within the scope of M 5 it would also have to be considered that the WEEE Directive explicitly does not recognise interim storage as recovery. The interim storage of components containing minor metals is also not recycling as defined in the End-of-Life Vehicles Directive. It would therefore require the European legislator to become active, if the definitions of recovery and recycling are to also include interim storage.

At European level, the provision of the measures according to M 1 and M 3 as well as the dismantling instructions according to M 2 would also be feasible in implementing measures according to the Ecodesign Directive 2009/125/EC.

Conclusion: Effective measures with a high degree of obligation are M 2 in combination with M 1, which can be additionally strengthened through M 3 and/or M 4. The implementation effort for M 3 and M 4 in particular, however, is fairly high. Measures with overall favourable assessments, which could be implemented at low expense, are M 6 and M 8. Both measures also have positive effects on the recovery of other metals. However, the degree of obligation is significantly lower here.

Furthermore, higher-level primary measures with options for end-of-life vehicle dismantling facilities can increase the efficiency of in-house and inter-company logistics, especially the development and introduction of a recycling enterprise resource planning system (RERP), possibly supported by a level detection system, as well as working up a “lean management” handout.

The gross benefit potential from the view of climate protection, i.e. the greenhouse gas emissions from the extraction of the quantities of NdFeB magnets occurring as waste in Germany in 2020, is 4237 t CO_2eq (approx. 350 population equivalents). Material losses along the process chain and greenhouse gas emissions due to the recycling processes must be deducted from this. In view of this potential, the appropriateness of statutory provisions seems questionable from the view of climate protection. Possible other motivations can be other environmental burdens of the primary extraction, securing raw materials as well as increasing quantities in future. However, the assessment of these aspects must also take into consideration the expected substantial losses along the recovery chain.

3.2 Printed circuit boards, sensors and spark plugs containing precious metals separated from end-of-life vehicles

3.2.1 Waste streams and actual processes

Apart from removing components for marketing of used parts, vehicle electronics are currently not dismantled. Together with the residual chassis, they are input into shredder processes, in which the precious metals contained are largely lost.

Groke et al. (Groke et al. 2017) analysed end-of-life vehicles built in 2011 to 2014, which will not reach the recovery process in large numbers until around 2025. The study covered 114 component groups; however, these were not only selected due to their precious metal content, but also due to their content of minor metals such as neodymium. 30 components were analysed in depth. The three components to be considered with regard to the precious metal yield to be improved: printed circuit boards from vehicle electronics, lambda oxygen sensors and spark plugs, were also the subject of the analysis.

With regard to economic feasibility, separation was recommended for eight components, including components containing precious metals: lambda oxygen sensors and five control components containing printed circuit boards. For a further nine components, a clear decision for or against dismantling was not possible, including three control components containing printed circuit boards and two sensors containing precious metals (Groke et al. 2017; p. 195). Purchase offers already exist on the market for part of such removed components; the highest price by far, 6.50 €/kg is named for lambda oxygen sensors due to their precious metal content. Due to the low mass, however, the unit price is only 50 percent per probe (Groke et al. 2017; p. 158).

The electrodes of the spark plugs containing precious metals have a target metal content within the range of several milligrams per spark plug. Due to the high market price, the authors expect only a small market share for these spark plugs (Groke et al. 2017; p. 77).

The quantity of printed circuit boards per end-of-life vehicle distributed over the electronic components can be estimated with approx. 1 kg per vehicle, whereby significant differences exist depending on the vehicle type. Based on a rather optimistically assumed target metal content for printed circuit boards, the primary metal prices value is 9.54 €/kg printed circuit boards. The printed circuit board value would therefore be€ 9.54 per vehicle. However, this is not the remuneration that an end-of-life vehicle dismantling facility would actually received, because:

- The costs of the intermediaries and the companies in the further recovery chain through to extraction of the precious metals (electrical and electronic equipment treatment companies, copper mill) must be financed from the revenue.
- The costs for the small quantity pick-up logistics must be financed from the remuneration. Even if this pick-up takes place at the same time as other waste, part of the total effort must be financed from the revenue.

- Losses occur in the treatment chain.

This explains why Groke et al. (Groke et al. 2017; p. 129 ff .) use wholesale revenues of 2.80 €/kg for printed circuit boards from end-of-life vehicles.

Above all, a large number of printed circuit boards and electronic components cannot be removed with justifiable effort. The actual potential revenue per end-of-life vehicle is thus significantly below the above-named value.

The total potential from printed circuit boards for a current return of approx. 500,000 end-of-life vehicles per year in Germany with a primary metal prices value of € 4.77m/a. Part of this can be recovered with justifiable effort through dismantling.

However, the estimation of the potential must also take into consideration that precious metals are already recovered from shredder fractions. Reliable information about the yield is not available. Schüler et al. estimate it to be 20 to 25% (Schüler et al. 2017 p. 35).

An increased use of electronic components with increasing requirements is to be expected in the future. This initially speaks in favour of growing quantities of printed circuit boards. As the sizes and precious metal content of printed circuit boards reduce continuously, among other things due to miniaturisation, nonetheless, a growing precious metal potential from printed circuit boards is not to be assumed for end-of-life vehicles.

As elaborated by Groke et al. (Groke et al. 2017), moreover, the removal of a limited selection of electronic components can be economically efficient from the revenue for the material obtained. The number of components, for which a dismantling recommendation is given is however very small and the dismantling times can vary considerably depending on the end-of-life vehicle type.

Schüler et al. (Schüler et al. 2017) specifically examined the treatment of power electronics from electrical vehicles. These components are characterised by a high concentration of electronic functions and thus of printed circuit boards and in today's vehicle models by comparatively good accessibility. Due to the expected strong growth of the e-vehicle market, growing quantities are to be expected to be generated by these end-of-life vehicles in the future. The authors tested the breaking open of the housings and detaching of the components they contain, in particular the printed circuit boards, by means of an impact mill with subsequent sorting out of the printed circuit boards and give – rather optimistically estimated - precious metal yields of 98%. Here too, according to the authors, the process is economically feasible, yet the cost-revenue balance of the end-of-life vehicle shredder route proves to be significantly better (Schüler et al. 2017; p. 37f.).

Furthermore, it must be noted that motor vehicles – as well as equipment installed in them and which cannot be separated from them without disproportionate effort and which can only fulfil their function specifically as part of the motor vehicle – do not come within the scope of ElektroG, but, where they are class M1 or N1 vehicles or three-wheel motor vehicles (and not mere motorcycles), including their components and materials, are covered by the End-of-Life Vehicle Ordinance.

In addition to the dismantling effort, another obstacle is that only a small quantity of vehicle electronics or lambda oxygen sensors occur in each end-of-life vehicle recovery facility. Accordingly, it takes a long time before collection containers, for example, wire mesh box es are full and can be provided for pick-up. However, multiple pick-up of smaller quantities over the year would lead to significantly higher logistics costs. The industry reports that several end-of-life vehicle recovery facilities include separated out lambda oxygen sensors in the deliveries to the treatment companies for catalytic converters containing precious metals, who have good access to precious metal recovery. It is not known to what extent this is done.

3.2.2 Technical target recovery chains

Electronic scrap treatment processes, which are largely already available, can be used to recover precious metals from electronic components. These are roughly divided into two process steps

- Stage 1: Treatment of electrical and electronic equipment. In this stage, three groups of processes can be essentially used:
    1. Manual removal of printed circuit boards
    2. Breaking open housings and exposing the printed circuit boards and other components they contain, e.g. in impact mills or other suitable units with subsequent manual or even automatic sorting
    3. Direct feed to shredder and separation processes designed for the treatment of electronic scrap without high-quality printed circuit boards
- Stage 2: Recovery of the precious metals from the printed circuit boards or precious metal-rich sorting fractions acquired in stage 1. This treatment step takes place in copper mills (main quantity) or other metallurgical processes.

Waste from end-of-life vehicles containing precious metals should be added to this process chain if they are suitable for this and as a result, significant improvements to the precious metal yield are to be expected, compared to the current shredder route for residual chassis. Processes that use, for example, impact mills to break open the housings, are probably not yet in operation, but can be realised quickly.

The manual dismantling of the removed vehicle components for the separation of printed circuit boards is also not recommended for economic reasons, according to the results of Groke et al. (Groke et al. 2017) and Schüler et al. (Schüler et al. 2017).

The breaking open of housings by impact mills or similar with subsequent sorting should take place in electronic scrap primary treatment facilities, which have appropriate technology and process the vehicle material there, possibly campaign-wise. However, it should be noted that flexible potting compounds, frequently used on printed circuit boards in vehicles, among other things as vibration protection, can cause difficulties in crushing plants.

Due to the small quantity of spark plugs containing precious metals, a separate dedicated treatment path is not expedient. Spark plugs can be processed directly in copper mills, but due to the high fraction of ceramics and metals not usable by copper mills also the low total quantity, this is also not possible as an individual fraction. Direct addition to high-quality printed circuit board fractions would reduce the value of the printed circuit board batches. Feeding into shredder processes would generally probably lead to loss of the precious metals contained, because these are in or on electrodes, which usually contain nickel or iron and so together with the precious metal fractions, get into the FE fraction with the magnet separation. Therefore, separate adapted treatment processes would be required. As long as such processes are not available, separation of spark plugs therefore does not seem to be advisable.

Lambda oxygen sensors are already partly removed and handed over to recovery facilities due to their comparatively high value.

As with the separation of vehicle electronics and the printed circuit boards they contain, recovery opportunities are also available here. The challenge therefore lies not in setting up recovery processes but in the poor economic feasibility of separation and logistics.

3.2.3 Quantity structure and logistical analysis of the waste streams

The recycling chain begins with the take-back of end-of-life vehicles. These can be returned to officially approved acceptance facilities, collection facilities and dismantling facilities. There are several thousand collection points in total. The take-back process is already established. The end-of-life vehicles are transported from officially approved acceptance or collection facilities to dismantling facilities. This is where the dismantling of the vehicle electronics should take place. Dismantled electronics should then be transported to a treatment facility for WEEE and there they can be fed into existing recycling routes.

Unit labour costs or the time per removed electronic component are an important economic feasibility criterion for vehicle electronics.

Due to the clear position of the target objects, the removal times for lambda oxygen sensors are in a comparatively favourable relationship to the value of the probes, even if the time required for economic removal is also not easy to achieve. Time drivers are “tooling up costs”, i.e. preparation for the “lambda oxygen sensor removal” tasks, if this cannot be incorporated into the process. 20 kg quantity per year is too little to set up a separate, dedicated logistical solution. However, this 20 kg, calculated optimistically, represents a goods value of approx. € 480.

20 kg lambda oxygen sensors occur in the area of the logistics once a quarter. This corresponds to the order of magnitude of a standard parcel, which can be sent with a KEP (courier, express or postal) service for approx. € 12. Compliance with relevant regulations on separate handling of waste in the logistics process must be taken into consideration here (cf. DSLV 2015; in particular p. 14). Appropriate prerequisites would have to be created by the KEP service provider. The quantity is so small that – provided the prerequisites exist – existing logistics networks[2] can be used for the logistics. It is assumed that carriers still have sufficient load space. By using existing networks, in general, lower costs are incurred compared to setting up new networks. Nonetheless, with the low quantities generated, it can be assumed that the standard price of approx. 12 €/parcel must be paid. This is only economically feasible if approx. € 12 per delivery is acceptable. In addition, use of KEP service providers is only interesting if there are addressees who can integrate the material into an existing recycling process.

3.2.4 Consolidation level and level of motivation

In which form should consolidation take place (consolidation level)

The manual separation of printed circuit boards from electronic components is not recommended for economic feasibility reasons. The operation of a facility for opening housings, e.g. by means of an impact mill with subsequent sorting, is out of the question for end-of-life vehicle dismantling facilities due to the small quantity.

The consolidation should therefore be undertaken in the form of removed electronic components or lambda oxygen sensors. On pick-up, where possible lambda oxygen sensors should be collected at the same time, however, they should be kept separate.

The market players and their level of motivation

The central challenges lie in the following fields

- Removal is only profitable for end-of-life vehicle dismantling facilities for a small part of the electronic components.
- The total quantity that can be removed and processed economically is therefore very small.

[2] The KEP service networks, e.g. of DHL or Hermes, are made up of close-meshed coverage of the whole of Germany with pick-up and delivery relations as well as corresponding transfer points and depots.

- The total quantity occurring in the individual end-of-life vehicle dismantling facility and to be picked up for further processing is so small, that only a few pick-up operations with small individual quantities are required during the year.

End-of-life vehicle dismantling facilities: The small total quantity worth separating out makes it questionable whether the effort required to set up and coordinate the dismantling processes and to forward electronic components to WEEE recovery facilities is justifiable from the view of the end-of-life vehicle dismantling facility. The situation is more favourable for the removal and forwarding of easily accessible and relatively high-quality components such as lambda oxygen sensors, provided purchasers and logistics processes exist for these. If the cost of setting up and operating the dismantling and forwarding process cannot be refinanced from the revenues, it cannot also not be made economically feasible through efficient logistics. The specific amount of logistics costs to be expected depends on numerous factors and cannot be reliably given here.

Electrical and electronic equipment treatment companies: The small total quantity of electronics components is the main obstacle here too. It is questionable whether setting up a facility for breaking open the housings using an impact mill or upgrading existing facilities for breaking open aluminium housings is justifiable in business terms. This will probably only occur when a reliable supply of adequately large quantities of electronic components is secured. The setting up of a pick-up service for the components at the end-of-life vehicle recovery facility by the electrical and electronic equipment treatment facility is not a realistic assumption in view of the small quantity streams.

An important factor is also the pricing between the end-of-life vehicle dismantling facilities and electrical and electronic equipment treatment facilities. The pricing will have to be based on a delivered quantity of removed vehicle electronics. The composition of this quantity and which material values it contains are not known. Sufficient quantities for representative sampling to determine the precious metal content, for example, in copper mills, as well as the content, e.g. of aluminium will probably not be available. The pricing of the electrical and electronic equipment treatment facility will therefore have to include corresponding contingency mark-ups.

3.2.5 Scenario for a possible market-driven approach

A market-driven approach with substantial volume effect does not appear to be realistic for the waste streams considered here. A scenario with limited quantity effect could look like the following:

One or several primary electronic scrap treatment facilities set up a new process (impact mill, sorting) or adapt an existing process provided for other uses, in order to be able to treat vehicle electronics in campaign operation. They offer a remuneration for vehicle electronics based on daily fixed prices, which is linked to minimum quality requirements.

Interested end-of-life vehicle dismantling facilities separate out easily removable components containing precious metals and consolidate them with components, which have been separated for used part sales, but have proven to be damaged.

Companies which already operate or commission disposal logistics in the area surrounding the end-of-life vehicle dismantling facilities, offer to pick up the vehicle electronics in cooperation with primary electronic scrap treatment facilities. The following, for example, would be conceivable here.

- Workshop or garage disposal facilities, which could also add defective control devices from vehicle workshops and garages in order to achieve somewhat larger quantities or
- companies, which pick-up and recover other waste containing precious metals (e.g. catalytic converters) from end-of-life vehicle dismantling facilities.

Conclusion: The economic potential for the stakeholders is very small in amount and reliability. The realisation of more comprehensive market-driven activities appears unlikely.

3.2.6 Regulatory measures

The following measures could be useful for increasing the recovery of precious metals from vehicle electronics:

- M 1: Design specifications for the vehicle industry

Obligation regarding dismantling-compatible installation (see e.g. VDI Guidelines 2243: Recycling-orientated product development) of larger electronic components in vehicles; to be anchored in the European End-of-Life Vehicles Directive and in the German End-of-Life Vehicle Ordinance, if applicable in the form of additional or added annexes; only productive in combination with an dismantling obligation for end-of-life vehicle dismantling facilities.

Limitation to relevant components, in order to avoid unreasonable expense; the separation recommendation of Groke et al. (Groke et al. 2017) could serve as an initial basis to identify the relevant components.

To be considered: It should first be investigated, to what extent trade-offs can occur with the weight reduction and material efficiency design objectives.

- M 2: Dismantling, recovery and information obligation

Obligation to dismantle larger vehicle electronics components and to feed them into a recycling process, in which the printed circuit boards are separated and are passed on for precious metal recovery; anchored in the End-of-Life Vehicles Directive, Annex I (Minimum technical requirements for treatment) No. 4 (Treatment operations to promote recycling) or in the Annex to the German End-of-Life Vehicle Ordinance.
If new requirements for the separation of components containing precious metals from end-of-life vehicles within the scope of the dismantling were to be specified by law, this would also mean that the manufacturers would have to provide appropriate added dismantling instructions for the dismantling facilities, which explain how these components containing precious metals can be dismantled.

- M 3: Improve the return of end-of-life vehicles

Increases the potential for the recovery of precious metals, not only in case of dismantling parts containing precious metals but also – with significantly poorer yields - on shredding non-dismantled components that are still in the end-of-life vehicles.

- M 4: Shredder optimisation

Promotion of projects for the improvement of precious metal yield (as well as the yield of other metals such as steel, copper and aluminium) from shredder fractions in case of components containing precious metals that are not dismantled; e.g. by calling for proposals for a research project with the participation of industrial partners.

- M 5: Consolidation/ pooling workshops

Within the scope of consolidation workshops, opportunities will be worked up for using and expanding existing networks, see also Figure 2. It could be useful to bring together dismantling facilities (and possibly other companies with similar waste from other industries) with their potential customers and logisticians to extend existing or to develop new networks. The objective is for appropriate agreements to be made in order to use already established pickup relationships and to set up new connections.

- Primary and general measures

Furthermore, several general, primary measures addressing end-of-life vehicle dismantling facilities can increase the efficiency of in-house and inter-company logistics, especially the development and introduction of a recycling enterprise resource planning system (RERP), possibly supported by a level detection system, as well as working up a "lean management" handout.

Assessment of the measures:

Compatibility with EU law: Measures M 1 and 2 would extend beyond the range of obligations defined to date in the End-of-Life Vehicles Directive. Adjustment of the European regulatory instruments would therefore be required and/or tightening the German regulations. Such a German over- implementation is possible in principle due to the objectives of the End-of-Life Vehicles Directive, the high level of protection for the environment provided for in Art. 114 Para. 3 and 191 of the Treaty on the Functioning of the European Union ("TFEU") and the "reinforcement of protection" clause of Art. 193 TFEU. However, it would have to be ensured that these legislative measures do not have a negative effect on smooth functioning of the internal market or cause competitive distortions.

Conclusion: The only effective measure with high degree of obligation and overall favourable assessment is M 2. However, the implementation expense here is fairly high. Measures M 3, M 4 and M 5 have favourable assessments overall. These measures also have positive effects on the recovery of other metals, however, the degree of obligation here is rather small.

The gross benefit from the view of climate protection, i.e. the greenhouse gas emissions from extraction of precious metals occurring as waste quantities of vehicle electronics in Germany in 2020

is 3,834 t CO_2eq (approx. 350 population equivalents). Material losses along the process chain and greenhouse gas emissions due to the recycling processes must be deducted from this. In view of this potential, the appropriateness of statutory provisions seems questionable from the view of climate protection. Possible other motivations can be other environmental burdens of the primary extraction or the securing of raw materials. However, the assessment of these aspects must also take into consideration the expected substantial losses along the recovery chain.

4 The consolidation of other waste streams containing precious and minor metals

4.1 Environmental catalysts containing precious metals

4.1.1 Waste streams and actual processes

In Germany, approx. 800 t PGM catalysts occur annually (Hassan 2003; p. 25), of which approx. 30 t/a in environmental processes (Hassan 2003; p. 74). In most cases, the precious metal content lies between 0.05 and 10 %, in flue gas and exhaust air cleaning processes it is also often below 0.02 %.

The recovery of precious metals from catalysts is already standard practice. This does not include catalysts with very small precious metal concentrations, as economic recycling is only possible from approx. 0.01 % (in the case of platinum catalytic converters). Large companies mainly use existing connections to recycling companies and almost always opt for recycling (Hassan 2003; p. 25).

In general, the recovery process is designed at the same time as the development of new catalysts. In most cases, the take-back of the used catalysts is arranged through long-term agreements between the chemical company and the manufacturer of the catalysts. The manufacturing company is often also the recycling company. It is also particularly favourable for the recycling that the number of consumers in the chemical industry is small and the quantity per consumer is relatively large, as a result of which the cost of collection is relatively low (Hassan 2003; p. 25).

One exception is environmental catalysts, which are used in small individual quantities, for example in combined heat and power plants or are used for catalytic after-burning. Catalytic converters from these applications are primarily added to steel scrap or the residual waste. The precious metal content is therefore almost completely lost.

4.1.2 Technical target recovery chains

Precious metal catalysts are already almost completely recycled. The total precious metal losses are assumed to be below 4 %. Losses in the processes process, losses due to the removal of catalysts with low metal content and losses during recycling are taken into consideration (Hassan 2003; p. 74).

Environmental catalysts from decentralised applications can be added to the existing recycling processes. It is not necessary to develop technical processes.

4.1.3 Consolidation concept

The central logistics challenge is increasing the collection rate, in order to obtain more mass in an established process for the recovery of precious metals from catalysts. In addition, on the one hand, the information of the operators of plants in which environmental catalysts are used is required regarding their precious metal content and return possibilities. On the other hand, the take-back process should be designed to be as low-threshold and simple as possible for the plant operators.

A conceivable solution would be to make the catalysts accessible to interested treatment facilities or agents on a first-come, first-served basis: A QR code is used to report the removal of the catalyst to a portal for pick-up. Whoever wants to pick-up the reported catalyst, must pledge the pick-up first. If a pick-up is not pledged within a certain time, a local treatment facility is assigned and the pick-up is initiated at their cost. Acceptance of this procedure represents the entrance ticket to the system. The platform could be set and maintained up via an operator, who is jointly contracted by manufacturers or treatment facilities. It could be financed through a charge per picked-up catalyst.

However, it is questionable whether the value of individual catalysts is sufficient to motivate the setting up of such or other systems and to participate in them.

Information needs

Apart from the data required to organise the logistics, information needs are seen in only one area: Catalyst users need information that the catalysts contain precious metals and about return possibilities.

4.1.4 Measures

A round table discussion initiated with catalyst manufacturers and representatives of catalyst users could help to develop the possibilities of providing improved information for users and for developing the take-back possibilities. In these discussions, the QR code approach outlined above could be introduced as an action option.

As environmental catalysts exist in separated form anyway after the exchange and are therefore easily accessed and recoverable, it should be checked whether the introduction of a statutory obligation for separate collection is advisable, e.g. by introducing extended producer responsibility for manufacturers and importers or, where the environmental catalysts occur as commercial waste: Extension of the Commercial Waste Ordinance (Gewerbeabfallverordnung) to include obligations for end users, in whose business the environmental catalysts occur as waste. If the environmental catalysts are hazardous waste according to the Waste List Ordinance (AVV), these must already be kept separate from other waste under current law. Mixing separately occurring, hazardous waste with other categories of hazardous waste (=hazardous waste with another AVV waste code) or with other waste, substances or materials is basically not permitted under sec. 9 para. 2 KrWG.

4.2 Waste streams containing cerium and lanthanum

4.2.1 Waste streams and actual processes

Table 6 shows the potential quantities and value of cerium and lanthanum from different areas of use.

Table 6: Potential quantities and value of cerium and lanthanum from different areas of use for the year 2020

Scope	Quantity Ce[1)]	Quantity La[1)]	Quantity and value Total cerium and lanthanum [2]				Trend
	Germany		Germany		Germany & neighbouring states (in brackets: EU total)		
	[t/a]	[t/a]	[t/a]	[k€]	[t/a]	[k€]	
Polishing compounds	90	3	93	419	237 (465)	1048 (2095)	constant
Separated FCC catalysts	80	170	250	1125	638 (1250)	2869 (5625)	constant
Separated out automotive catalytic converters	120	8	128	576	326 (640)	1469 (2880)	constant
(NiMH) batteries	120	52	172	774	439 (860)	1974 (3870)	constant
Special glass / ceramics	?	?	?	?	?	?	constant
Total	**> 410**	**> 233**	**> 643**	**2894**	**>1640 (>3215)**	**>7380 (>14470)**	

[1] Quantity data from Sander et al. (Sander et al. 2017; p. 35)
[2] primary metal prices Ce 4.5 €/kg; La: 4.5 €/kg (Source: USGS 2017)

The information on the content of cerium and lanthanum are to be viewed as an approximation, as there can be substantial spread in composition within the application groups. Reliable figures are not available for all waste streams.

The use and fate of cerium and lanthanum in polishing sludge

Typical fractions of the target metals in the polishing sludge after use are approx. 22.1 % by wt. cerium and approx. 17.8 % by wt. lanthanum (Sander et al. 2017; p. 363). With a total potential of 90 t cerium (Sander et al. 2017; p. 310) aa total quantity of polishing sludge dry mass for the year 2020 of around 400 t/a results. The quantity of waste is larger due to the water content and the abraded glass.

CeO_2 is suspended in water for grinding glass surfaces. Typical particle sizes lie between 0.5 and 1.5 µm. The CeO_2 content after polishing is between 5 and 80 % (Adler, Müller 2014; p. 132). Other constituents are abraded material and water. Alternatively, in case of supply bottlenecks or for cost reasons, ZrO_2 or Al_2O_3 are also used.

Polishing sludges are usually recirculated by the companies that use them. When the polishing effect recedes, the sludges are dewatered and are generally placed in landfill.

The use and fate of cerium and lanthanum in special glass and ceramics

Cerium is used to decolour glass. Lanthanum is also used to produce glass with a high refraction index and high clarity. The main area of use is primarily radiation shielding glass and laser glass. The cerium concentrations here are approx. 1-2% (Sander et al. 2017; p. 176ff). The glass is currently not separated and recovered. No reliable figures are available on the quantity of special glass and ceramics that occur annually in Germany.

Rare earth metals are also used in abrasive ceramics / media and ceramic heat-resistant coatings in gas turbines. However, only some of the abrasive ceramics contain cerium. In this area of use, cerium has no particular relevance for the German market. The same applies to heat-resistant coatings (Sander et al. 2017; p. 257ff).

This waste stream was therefore not pursued further.

Use and fate of cerium and lanthanum in separated out FCC catalysts

Rare earth metals are used as promoters in FCC catalysts (FCC: Fluid Catalytic Cracking) in the petrochemical industry. The largest fraction by far is lanthanum, which is used to dope zeolites. Zeolites for catalytic cracking can contain 2-3.5 % rare-earth metal oxides (Sander K. et al. 2017; p. 132). Rare earth metals are also added to the α - Form of the aluminium oxide to increase the surface activity to above 1000 °C. The annual total consumption of zeolites for catalytic cracking is estimated to be 9,400 t (Hassan 2003; p. 11). In Germany, most of the zeolites are added to cement works.

Use and fate of cerium and lanthanum in separated car catalytic converters

Cerium and lanthanum oxides are used for thermal stability of the body in automotive catalytic converters. In addition, cerium is used in the form of a CeO_2/Ce_2O_3 mixture as an oxygen regulator. Car catalytic converters are already removed and treated as part of the end-of-life vehicle treatment. However, the treatment is concentrated on the precious metals. In the smelting process used, the rare earth metals are found in the slag. The slag is used as a construction material. In Germany, approx. 3,000 t slag occur from the recycling of automotive catalytic converters. These contain < 2.5 % cerium and < 0.5 % lanthanum (CUTEC 2016).

The use and fate of cerium and lanthanum in NiMH batteries

Cerium and lanthanum are used in batteries to increase the hydrogen storage capacity. The typical content is between 7 and 10 %. The take-back of batteries in Germany is specified in the Battery Act (Batteriegesetz - BattG). In 2012, approx. 530 t (Sander K. et al. 2017; p. 358) Ni(MH) batteries were collected via the battery take-back systems. After sorting according to the electrochemical system, the batteries are predismantled and are treated mechanically. Plastics are removed. The metal mixture is then generally used in the steelworks. The rare earth metals contained are lost.

4.2.2 Technical target recovery chains

Polishing sludge

After the separate collection of the polishing sludge by the producer, it is generally dewatered. The polishing sludge could be added to a central treatment plant relatively easily by the disposal company to recover the rare earth metals.

After crushing the filter cake, contaminations such as glass residues could be removed using dissolving processes. Pyro or hydrometallurgical processes can then be used to recover the rare earth metals. However, in view of the low added value and the small quantities, the expenditure required for this cannot be presented. In addition, there is often no separation of polishing sludge and abrasives in the companies, which leads to further contamination, e.g. with corundum, the separation of which is partly problematic in the process.

Use, for example in ceramic glazes, where cerium could be replaced 1:1, would be far less complex. However, here it must be noted that polishing sludges not only differ in composition but, depending on the area of use, also contain all constituents of the machined glass due to the abraded glass material. It therefore depends on the individual case, whether the contained substances prevent the planned use.

Use for producing mixed metals in foundries also is a conceivable application, in which cerium would be replaced 1:1.

Separated FCC catalysts

After collection, the treatment of catalyst residues could take place using hydro or pyrometallurgical methods in a central treatment facility.

Separated catalytic converters removed from cars

Automotive catalytic converters are already removed and dismantled. After crushing, the rare earth metals in the slag residues that occur during the treatment could be recovered by a central treatment facility using hydrometallurgical methods. The recovery of rare earth metals from slag is examined in the MinSEM project (CUTEC 2016).

NiMH batteries

The mixed metal scrap containing rare earth metals that occurs in the treatment of NiMH batteries can be further treated by a central treatment facility. There are several studies that have examined the recovery of rare earth metals from batteries. An overview is given by Binnemans et al. (Binnemans et al. 2013; p. 1-22). The company Umicore, together with Rhodia, announced in 2011 that the two have developed a process for the recovery of rare earth metals from NiMH batteries. The process is based on the ultra-high temperature process of Umicore. A pilot plant with an annual capacity of 7,000 t was started up in Hoboken (Belgium). In addition to NiMH batteries, the plant can also recover Li-ion batteries. After the pyrometallurgical separation of nickel, cobalt, copper and iron, the slag containing rare earth metals is treated. The rare-earth metal concentrates extracted can be used in the rare-earth metal separation plant of Solvay (formerly Rhodia) in La Rochelle (France) (Sander et al. 2017; p. 361).

4.2.3 Quantity structure and logistical analysis of the waste streams

Polishing sludge

The disposal chain currently begins with collection in the optical industry. Landfilling by the disposal company takes place in the next step. There is currently no treatment and it would have to be implemented as a process after the collection.

Separated FCC catalysts

FCC catalysts are used for cracking in the petrochemicals industry. As these are used in around 13 refineries in Germany (Petroleum Industry Association 2018), the used catalysts are also concentrated in a few locations. The collection process is already established. The catalysts are later used in cement works or are placed in landfill. No treatment takes place at present.

The collection system could continue to be used for the recovery of the catalysts. At the same time, the destinations change: Instead of landfills, the transport is to treatment companies. As a smaller number of these exist in Germany than landfill sites, the distances will be longer. This generally drives the logistics costs, however, to a significantly disproportionately small extent compared to the transport distance. To keep the costs under control, it is recommended that the catalysts be stored until whole loads are reached. With 13 refineries and 9,400 t quantity generated per year, 723 t per refinery are to be assumed. This is equal to approx. 18 articulated trucks (á40t) per refinery and thus a monthly transport frequency of one articulated truck. From this the storage requirement is 40t for 20 days. It can be assumed that this is not problematic in the existing facilities. A system, in which it is possible to store directly in the semi-trailer or a special semi-trailer would need to be checked, which reduces the loading time on pick-up.

A rail connection can be assumed for refineries and central treatment companies. This is generally used to transport the petrochemical products from the plant and to deliver voluminous material flows to treatment facilities due to the large-scale industrial processes. 1,600 t (40 times the capacity of a truck) have to be collected to fill a whole train. This would require a storage volume equal to the generated quantity of around two years . This reduces transport costs massively, but leads to storage costs and loading efforts. This is therefore only considered to be practicable if the storage areas and loading possibilities for rail loading already exist.

However, this will only take place if investment is made in a treatment facility for the recovery of rare earth metals. It will be decisive whether this investment pays.

Separated catalytic converters removed from cars

Catalytic converters are removed from end-of-life vehicles returned properly for recovery, and the precious metal fractions are added to the metallurgical recovery. The rare earth metals collect in the slags contained in them. The final step in the chain is the separation of the target metals from these slags.

Treatment of the target metals cerium and lanthanum is logistically uncritical, as the starting materials already exist in consolidated form in the central treatment facilities.

Whether an investment is made in a treatment plant will be decisive.

4.2.4 Consolidation concept

A consolidation of waste from all sources to increase the processing quantities would therefore hardly be productive, because a single treatment process would not be suitable for the very differently composed waste streams.

The greatest challenge for the realisation of treatment processes for all waste streams containing cerium and lanthanum is the low value of the metals. Economic solutions, which would involve the development of time-consuming treatment processes requiring intensive investment costs, are therefore not in sight.

Analysis of the individual quantities leads to the following results:

- FCC catalysts: Due to the low concentrations of the metals in the catalysts, recovery with reasonable cost or effort does not seem possible. Thus, the waste streams containing cerium and lanthanum, which have the greatest potential quantity, are to be omitted.
- Special glass and ceramics: The small concentrations of the target metals in particular, as well as the individual quantities, are arguments against consolidation and the setting up of a recovery solution here too. In addition, the radiation shielding glass contained in the partial waste stream is radioactively contaminated.
- NiMH batteries: Processes for the recovery of the mixed metal fraction from the treatment of batteries are available in principle. However, they are not realised due to the low material value and large effort required to extract the rare-earth metal concentrates. Quantity consolidation within the NiMH batteries group already largely exists due to the treatment of batteries in few locations.
- Automotive catalytic converters: The slags from the treatment of automotive catalytic converters already exist in consolidated form in the catalyst recovery facility. Further quantity consolidation with other waste streams does not seem appropriate due to the required differences in the treatment processes.
- Polishing sludge: Here also, the large effort with low material values is an obstacle to treatment with the objective of extracting rare-earth metal concentrates. At the same time, however, due to the high cerium content in the sludges, recovery paths that are significantly less complex are possible, namely use in ceramic glazes or in foundries. The realisation of these paths is also

hindered by economic considerations, however, the threshold is significantly lower here. In addition, reservations regarding possible minor constituents in the sludges, which could impair the product or process quality during processing, appear to be more important. Here it should be checked whether consistent and transparent analysis and quality assurance measures along the value-added chain, from the occurrence of the sludges through to their use in ceramic glaze or foundries, can exclude disturbing contamination. The possibility of obtaining product status for this waste after appropriate (least complex possible) treatment and quality assurance should also be checked. In this way it could be possible to strength the trust of potential purchasers in the material and to develop a market for it. However, when consolidating individual quantities, an eye must definitely be kept on the differences in the composition of the polishing sludges. Such differences will occur in sludges of different users of the polishing sludge, but they are also possible over time in a single source, for example, due to a change in product range or changes in the processes.

4.2.5 Measures

Initiation of a workshop with potential stakeholders of the process chains for the use of polishing sludges in ceramic glazes or foundries. Potential participants could be particular companies, who use large quantities of polishing sludge, foundries, manufacturers of ceramic products and possibly disposal companies.

4.3 Phosphors containing rare earth metals

4.3.1 Waste streams and actual processes

Table 7 shows an overview of the potential of rare earth metals in phosphors from fluorescent lamps, CRT monitors and LCD monitors.

Table 7: Potential quantities and value of rare earth metals in phosphors from different areas of use. The derivation of the potential quantities in Germany is explained in the text.

	Quantity and value of rare earthmetals				
	Germany		Germany & neighbouring states (in brackets: EU total)		Trend
Scope	[t/a]	[k€]	[t/a]	[k€]	
Fluorescent lamps[1]	20	1800	51 (100)	4590 (9,000)	falling
CRT monitors[2]	3.75	364	9.6 (18.75)	928 (1820)	rapidly falling
LCD monitors[3]	0.4	42	1 (2)	107 (208)	falling
Total	**24.15**	**2206**	**61.6 (120.75)**	**5625 (1028)**	**falling**

[1] Fluorescent lamps: REM fractions in REM phosphors market mix World: Y 64%; Ce 17%; Pr 6%; La 5%; Eu 4%; Gd, Tb, Nd 2% each; Er 1% (European Commission 2014; p. 154) primary metal prices value REM in the REM phosphor mix: 90 €/kg (Y €39, Eu €2, Tb €13, Pr €7, others €6)
[2] CRT devices: Typical REM fractions in phosphor: 23.2% yttrium and 1.5% europium

[3] LCD monitors: REM fractions in REM market mix for phosphors: 64% yttrium, 17% cerium, 6% praseodymium, 5% lanthanum, 4% Europium, 2% each gadolinium, terbium and neodymium, 1% erbium; primary metal prices value of REE: 104 €/kg REM mix;
Note: Source for REM prices: USGS 2017

Fluorescent lamps

Rare earth metals are used in phosphors for fluorescent lamps. The fraction in the lamps is approx. 1-3 % by weight phosphor. The phosphor contains approx. 10-20 % rare earth metals (Luidold et al. 2013; p. 227). In 2014, approx. 6,800 t gas discharge lamps were collected (BMUB 2017), which corresponds to a quantity of 68 – 204 t phosphor. With phosphor's assumed 2 % share of the lamp mass and an assumed rare-earth metal fraction of 15 % in phosphor, the quantity of rare earth metals is 20 t/a.

In recent years, fluorescent lamps have been increasingly displaced by LED lamps. The production of gas discharge lamps has fallen drastically. The quantity placed on the market in Germany has fallen by more than 40% since 2014. Today, lamps are returned that are around 10 years old. In 15 to 20 years there will probably still be around one billion lamps in the market and thus still great quantities of phosphors will occur.[3] However, the quantity will fall continuously.

The collection of fluorescent lamps is specified in the WEEE Directive/ ElektroG. Fluorescent lamps are mostly collected together with other lamps (e.g. LED retrofits) in collection group 4 (until November 2018). After the collection the lamps are sorted by type by a treatment facility. The fine fraction containing phosphor is separated out in the further treatment and is currently placed in landfill.

CRT monitors

CRT monitors contain between 7 and 15 g phosphor per screen (Luidold et al. 2013; p. 13). With an average weight per unit of 28 kg (Jehle 2011; p. 17), the percentage by weight of phosphor in the screen is 0.025 – 0.05 %. In 2007, 1,435,000 CRT monitors were sold in Germany (Jehle 2011; p. 6). With a use period of 10 years, this equals a total waste quantity of 40,200 t CRT monitors or 10 to 20 t phosphors a year, which have a typical content of 23.2% yttrium and 1.5% europium. The rare-earth metal quantity is thus approx. 2.5-5.0 t/a. The phosphors essentially consist of halophosphate, zinc sulphide and rare earth metals (e.g. yttrium, europium). The collection of CRT monitors in Germany is specified in the ElektroG. They are collected together with other screens and monitors in collection group 3 (collection group 2 as of December 2018). CRT monitors were displaced from the market by the introduction of flat LCD, plasma and LED screens. Waste quantities have therefore fallen sharply in recent years.

After transport from the collection centre to one of the 439 WEEE primary treatment facilities (ear-Portal 2018) for waste electrical and electronic equipment, they are first sorted by device type. The front and funnel glass is then separated, e.g. using the hot wire method. The phosphor layer is then extracted. According to Annex 4 No. 4 lit. a ElektroG, the fluorescent coating of cathode ray tubes must be removed. The different types of glass as well as separated metal parts can be recovered. The phosphor layer is generally disposed of in landfill sites.

LCD monitors

Phosphors containing rare earth metals are used in the CCFL background lighting of LCD monitors. The quantity and size of the CCFL capillary tubes are highly varied. While only one tube on average, with an average weight of 1 g per tube, is used in notebooks, 15 tubes with an average weight of 4 g each are used in televisions. Each capillary tube contains approx. 2.1 % phosphors. The rare earth

[3] Information received in person from Lightcycle Retourlogistik und Service GmbH

metals (mainly yttrium and europium) account for approx. 10 % of phosphors (Buchert et al. 2012; p.10).

In 2016, a recycling quantity of approx. three million units was expected, based on sales figures and an average use period of eight years (Fröhlich 2015; p. 316). With an average weight of 6.9 kg (Bakas et al 2016; p.21), this gives a total quantity of units of 21,075 t waste equipment in 2016. With a share of 0.31-0.93 % (Fröhlich 2015; p. 315) background lighting per unit, the total quantity of background lighting is 65-196 t in 2016. With a typical content of 0.13 g rare-earth metal oxides per unit (Buchert et al., 2012; p. 11), the mass of rare earth metals is 0.4 t/a. A downturn in the returned quantity is to be expected in future years to approx. 2,900,000 units in 2020.

LED technology has been used increasingly for the background lighting for several years. LEDs also contain phosphor containing rare earth metals, however with a significantly smaller quantity.

The collection of LCD monitors in Germany is subject to the Electrical and Electronic Equipment Act (ElektroG). They are collected together with other screens, monitors and TVs in collection group 3 (collection group 2 as of December 2018). After they have been transported to one of the 439 primary WEEE treatment facilities (ear portal 2018), the different types of units are separated. According to Annex 4 No. 1 lit. j ElektroG, the liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 cm^2 and all those back-lighted with gas discharge lamps are to be removed. In addition, gas discharge lamps must be removed from collected waste equipment. After separation, the CCFL lamps are fed into general lamp recycling. After removing mercury, the phosphors with possible contamination due to broken glass, mercury and other materials are generally placed in landfill (Buchert et al. 2012; p. 21).

4.3.2 Technical target recovery chains

The separation of phosphors from fluorescent lamps, CRT monitors and LCD monitors is already standard practice. The phosphor powder could be collected and added to a joint recovery process through a central treatment facility. Here the rare earth metals can be separated using hydrometallurgical methods. An overview of recycling concepts for phosphors is given by Binnemans et al. (Binnemans et al. 2013; p. 1 – 22).

4.3.3 Quantity structure and logistical analysis of the waste streams

Gas discharge lamps

The recycling chain begins with the collection and take-back of waste lamps. These can be returned to municipal collection centres, producers, stores and the electrical trade. In total, there are more than 11,000 collection centres (deduced from German Environmental Agency 2018b). Direct picking up also takes place. The take-back process is already established. All lamps are then sorted by type. The phosphors are then separated out. In this way they could be treated to produce marketable products.

LCD monitors

The recycling chain begins with the take-back of the waste electrical and electronic equipment (WEEE). These can be returned to municipal collection centres, producers, stores and the electrical trade. In total, there are more than 11,000 collection centres (deduced from German Environmental Agency 2018b). The take-back process is already established. The WEEE are later forwarded to a dismantling facility. There the LCD devices with CCFL background lighting as well as the lamps are removed, the lamps are sent to a waste lamp treatment company. This step is also already established. The last step in the chain is a recovery company, which treats the phosphors to produce marketable products.

4.3.4 Consolidation concept

Methods are available for further treatment of at least part of the phosphors to form rare-earth metal concentrates, but are currently not operated for cost reasons.

If the processes were to be started up again, the separated quantities available from existing treatment processes of lamps and equipment could be added to these facilities.

Consolidation concepts for separated phosphors extending beyond this are not useful, due to the low and declining quantity.

4.3.5 Measures

No measures are named for these waste streams.

4.4 Separated LCD layers containing indium

4.4.1 Waste streams and actual processes

Indium tin oxide (ITO) is used in LCDs. ITO is made up of approx. 90 % indium oxide and 10 % tin oxide. This corresponds to a mass fraction of 78 % indium in ITO. A tonne of the complete equipment unit thus contains approx. 12 g indium on average (Fröhlich 2015; p. 323). The percentage by weight of LCD panels of the unit lies between 5 and 8 % (Böni et al. 2015). With a calculated returned quantity of approx. three million units in 2016 and an average weight of 6.92 kg per unit, the total quantity of LCD panels is between 1,060 and 1,700 t a year. Here the mean value of 1,380 t is assumed. To estimate the potential of indium in LCD layers, the potential in Germany is derived from the world annual consumption of indium for LCD layers of 130 t[4]. Assuming that Germany's share of this quantity corresponds to Germany's share of the global GDP (4.5%), an annual potential for Germany is 6 t indium.

The collection of LCD monitors in Germany is subject to the Electrical and Electronic Equipment Act (ElektroG). They are collected together with other screens, monitors and TVs in collection group 3 (collection group 2 as of December 2018). After they have been transported to one of the 439 primary WEEE treatment facilities (ear portal 2018), the different types of units are separated. According to Annex 4 No. 1 lit. j ElektroG, the liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 cm^2 are to be removed. The complete manual dismantling of a device takes between 8 and 20 minutes. LCDs from which contaminants have been removed can be recovered in metallurgical processes or industrial waste incineration plants (Umweltpakt Bayern 2009). The indium contained in them is completely lost.

4.4.2 Technical target recovery chains

The collection of the units must ensure that transport to the primary treatment facility is as non-destructive as possible. LCD devices contain approx. 25 % plastic in the form of film on the outside. In a first step, the glass/plastic composite must be dissolved to extract the plastic-free glass fraction containing indium. This can be done by means of pyrolysis, physical-chemical separation methods or electrical disintegration. The indium can be recovered from the crushed ITO glass using pyrometallurgical or hydrometallurgical methods. Sellin et al. examined such a method for the recovery of indium from LCD terminals (Sellin et al. 2016; p. 163-175).

[4] Marscheider-Weidemann et al. 2016; p. 258

4.4.3 Quantity structure and logistical analysis of the waste streams

The recycling chain begins with the take-back of the waste electrical and electronic equipment (WEEE). These can be returned to municipal collection centres, producers and stores. The take-back process is already established. The WEEE are later forwarded to dismantling facilities. There the LCD devices are removed and the indium-rich glass fraction is extracted. This process partly already takes place. The last step in the chain is the so far unrealised treatment of the indium-rich glass fraction to produce a marketable product.

According to the developers, the semi-automated process developed by Sellin et al. enables more efficient dismantling of the units with separation of the glass fraction containing indium. The authors state that operation of such a plant requires larger throughputs than are currently achievable.

4.4.4 Consolidation concept

LCD devices are already removed and the indium-rich glass fractions they contain are already separated out. However, it is currently not possible to recover indium from the glass fraction. To this end, processes developed on a laboratory scale exist, but their implementation is not yet foreseeable.

A legal regulation could be useful, which obligates the primary treatment facilities to collect the glass fraction containing indium obtained from the treatment of LCD devices separately and to add them to an indium recovery process. It could be anchored in the WEEE Directive (Annex VII) or in the German ElektroG (Annex 4).

If such a process existed, this legal requirement would lead to pressure to act. The quantity consolidation would then result automatically from the fulfilment of the requirements.

However, this requires the appropriate methods to be made available. To strengthen the willingness to invest, it would be helpful for suitable separation methods to be developed further on a pilot scale. They should process real waste and based on this, a sound material flow balance should be worked up and an economic feasibility calculation performed.

4.4.5 Measures

Initiation of a research project on the implementation of the treatment of glass fractions containing indium from LCD devices on a pilot scale, with material flow and cost-effectiveness balances worked up for the production scale.

Creation of the possibility to set up long-term interim storage facilities.

Obligation of the primary treatment facility to collect the glass fraction from the treatment of LCD devices separately and to input them into a process for indium recovery; this could be anchored in the WEEE (Annex VII) or in the German Electrical Waste Act (ElektroG) (Annex 4).

4.5 Separated tantalum capacitors

4.5.1 Waste streams and actual processes

No reliable figures are available for the quantity of tantalum capacitors contained in printed circuit boards in WEEE that occurs in Germany.

The quantity of tantalum used in tantalum capacitors in Germany is estimated as follows: Germany's share of the gross world product (GWP) in 2014 was 4.5%.[5] Of the world production quantity of tanta-

[5]Derived from information in the online database of the United Nations Conference on Trade and Development (UNCTAD), dated 07.09.2017.

lum of 1,100 t in 2016 (USGS 2017; p. 167), around 60 %, i.e. approx. 660 t are used in capacitors. Assuming that the potential that occurs in a country corresponds to the share of the gross domestic product, the quantity for Germany is almost 30 t tantalum per year.

Nowadays, separated printed circuit boards are added to the precious metal recovery process. The tantalum contained in them is completely lost.

4.5.2 Technical target recovery chains

To enable dismounting, larger tantalum-rich printed circuit boards must be sorted out in the primary treatment facility. A trained eye is able to identify printed circuit boards with many tantalum capacitors with relative certainty. These tantalum-rich printed circuit boards would then have to be fed into one or several plants for dismounting and separation of tantalum capacitors. Suitable methods are available for recovery of the tantalum from the separated out capacitors. The operating companies of these processes already pay a remuneration for clean tantalum capacitors, depending on the current tantalum price.

4.5.3 Quantity structure and logistical analysis of the waste streams

The recycling chain begins with the take-back of the waste electrical and electronic equipment (WEEE). These can be returned to municipal collection centres, producers and stores. The take-back process is already established. The WEEE are later forwarded to a dismantling facility. Larger printed circuit boards must be removed there.

Tantalum-rich printed circuit boards would have to be sorted out here and added to a plant for separation of the capacitors by a WEEE treatment facility. Depending on the tantalum price, a market already exists for separated tantalum capacitors.

4.5.4 Consolidation concept

Consolidation would be possible by involving all primary treatment facilities. However, to do this, they would have to relinquish high-quality printed circuit boards, which they already sell profitably. Tantalum's share of the overall value is very small, it therefore offers hardly any motivation for such action. In addition, it would require significant sorting effort, which could not be reasonably paid for by potential purchasers of the printed circuit boards.

The printed circuit boards should therefore be sorted out by companies who possibly operate facilities for separating out the tantalum capacitors. For example, Electrocycling GmbH in Goslar set up a test plant on behalf of Deutsche Telekom and trialled a technology with good success, with which future tantalum capacitors can be separated from printed circuit boards from the dismantling of obsolete communication technology (bifa 2018).

This approach - and possibly others too - offer prospects of large quantities of tantalum-rich printed circuit boards that are relatively easy to access and, once the appropriate facilities are in operation, could attract further quantities from interesting market segments with an eye toward the target metals.

4.5.5 Measures

No measures are proposed for this waste stream.

5 Interim storage of waste containing precious and minor metals until recycling technology is available

5.1 Selection of suitable minor metals and waste streams

The waste streams preselected for analysis were assessed with the help of the following criteria with a view to possible long-term interim storage.

Criticality

The criticality of the supply of an economy with a raw material is generally assessed using the dimensions: supply risk and economic importance. The current report on critical raw materials for the EU assesses the supply risk for heavy rare earth metals (only Y and Dy are of interest here) as very high, the risk for light rare earth metals (La, Ce, Pr, Nd, Eu of interest here) as moderate. Indium tends to lie in the lower mid-range of the raw materials examined, i.e. compared to the rare earth metals it is assessed as being less critical. With regard to their economic importance, the relevant metals here do not differ significantly (European Commission 2014; p. 24, Fig. 5). In reference to the supply risk and economic importance, the following qualitative assessment can be derived from this (1 = very low, 5 = very high):

Indium (A: Supply risk: 2; B: Economic importance for Europe: 3)
➔ Merging the dimensions to form an indicator: A*B = 6

Cerium, lanthanum, neodymium, praseodymium, europium (A: Supply risk: 4; B: Economic importance for Europe: 3) ➔Merging the dimensions to form an indicator: A*B = 12

Yttrium, dysprosium (A: Supply risk: 5; B: Economic importance for Europe: 3)

➔Merging the dimensions to form an indicator: A*B = 15

The compositions of waste, e.g. of NdFeB magnets, differ significantly, including within individual application groups. A differentiated assessment of different areas of use and their typical compositions with regard to their supply risk and their economic importance is thus only approximately possible.

Greenhouse effect

The environmental relief potential results from the quantities of the target metals contained in the waste as well as the environmental burdens caused by extraction of the metals from primary raw materials. The greenhouse effect is used here as the main parameter for estimating the environmental effects.

Table 8 shows the results of the assessment of the waste streams to be considered.

Table 8: Preselected waste streams and their assessment; Potential without consideration of losses on collection and treatment and without consideration of the recovery effort; criticality of magnet applications with typical dysprosium content of approx. 10 % is assessed with 13, all others with 12; phosphors is assessed with 14 due to its high dysprosium content. Metal content <5% in brackets; n.d. = not known

Waste stream	Target metals criticality	Potential target metals (waste stream) Germany A (t)	Carbon footprint B (t CO_2eq/t target metals)	Carbon footprint of target metals in the waste stream A*B (t CO_2eq)
Indium				
LCD layers (In)	6	6* (138)**	225	**1,350**
Cerium/lanthanum				
Polishing sludge (optical industry) (Ce, La) (dry mass)	12	93 (400)	6.6	612
FCC catalysts (La)	12	250 (9400)	15.7	**3.940**
NiMH batteries (slags from the treatment) (Ce, La)	12	172 (n.d.)	16.1	**2,760**
Automotive catalytic converters (slags from the treatment) ((Ce), (La))	12	128 (3000)	7.2	919
Special glass / ceramics (Ce)	12	n.d.	7.4	n.d.
Rare earth metals from phosphors				
Phosphors from fluorescent lamps (Y, Pr, Eu, Ce, etc.)	14	20 (130)	20.3	405
Phosphors from CRT monitors (Y, Pr, Eu, Ce, etc.)	14	3.75 (15)	15.2	56.9
Phosphors from LCD (Y, Pr, Eu, Ce, etc.)	14	0.4 (4)	20.3	8.1
Rare earth metals from NdFeB magnets				
NdFeB magnets from hard drives, headphones, loudspeakers (Nd, (Pr), (Dy))	12	82.5 (275)	27.9	**2,300**

NdFeB magnets from industrial motors (Nd, Dy)	13	18 (60)	38.0	684
NdFeB magnets from motors of electric bicycles (Nd, Pr, (Dy))	12	7.2 (24)	29.1	209
NdFeB magnets from wind turbines (Nd, (Dy), (Pr))	12	3.3 (11)	32	106
NdFeB magnets from air-conditioning systems (Nd, Dy, (Pr))	12	2.7 (9)	29.3	79
NdFeB magnets from drive motors of e-vehicles (Nd, Dy)	13	3 (10)	34.9	105
NdFeB magnets from small e-motors from cars (Nd, (Dy), (Pr))	12	20.1 (67)	30	604
NdFeB magnets from medical equipment (e.g. MRT) (Nd, (Dy), (Pr))	12	3 (10)	31.1	93
NdFeB magnets from hub dynamos of bicycles (Nd, Dy)	13	1.5 (5)	36.9	55

Source for carbon footprint of metals: ecoinvent 2017; PloS 2014
* Annual consumption of indium for LCD 130 t; Assumptions: potential that occurs corresponds to the share of the gross domestic product (Germany 4.5 % of the total global GDP)
** Assumption: 10% of the LCD weight (1380 t)

Apart from the waste containing indium, the criticalities hardly differ. By contrast, the estimate of the environmental potential based on the lead parameter carbon footprint shows substantial differences. In many cases, there is a lack of reliable fundamentals for a sound forecast of the longer-term demand trend and thus of the quantity generated. Therefore, at this point, an indicative estimate only is possible.

- Indium
    - Despite the rather small quantity, due to the relatively high specific carbon footprint value, this group has a comparatively high environmental relief potential approximated by the carbon footprint main parameter.
    - The quantities of indium used in this area are expected to double by 2035 (Marscheider-Weidemann et al. 2016; p. 258).
- Cerium/lanthanum
    - FCC catalysts and slags from the treatment of NiMH batteries account for the largest part by far of the potential quantity and environmental relief potential. However, in view of the low concentration of the metals in the FCC catalysts, it is doubtful whether recovery is possible with reasonable effort.
    - Largely unchanged use quantities are also assumed in future for all the areas of use examined here.
    - The interim storage of special glass and ceramics does not seem appropriate due to the small quantities and concentrations. The same applies to FCC catalysts, which contain a large mass of cerium, however only in low concentrations. Slags from the treatment of NiMH batteries and automotive catalytic converters have higher concentrations of tar-

get metals. In view of the low material value of cerium and lanthanum as well as the foreseeable stable price situation, the future setting up development of a recovery process is not to be expected. This waste is therefore also not recommended for interim storage. Interim storage should only be checked for polishing sludge. The argument regarding the low value of the target metals also applies here, moreover, the total quantities are very small; however, due to the high target metal concentrations, the option of cost-effective recovery exists here by use in the ceramic industry and foundries.

- Rare earth metals from phosphors
  - The environmental relief of this group is roughly one order of magnitude smaller than the other groups due to the significantly smaller quantity. Fluorescent lamps make the largest contribution.
  - In all groups, the quantities used can be assumed to reduce in future.
  - Regardless of their origin, phosphors can be placed in storage under the same conditions, provided the waste is kept clearly and traceably separate according to sources, to enable a more targeted procedure for a future recovery facility.
- Rare earth metals from NdFeB magnets
  - The potential quantity and environmental relief potential is significantly dominated by IT products (hard drives, headphones and loudspeakers) as well as vehicle and industrial motors.
  - By 2027, the quantities used can be expected to triple.
  - Magnets can be stored under the same conditions, regardless of their origin, if no sales market exists (for example, as is to be assumed for large markets such as those from wind turbines) and the waste is kept separated according to sources in a clear and traceable way, to enable a more targeted procedure for a recovery facility at a later date, if this proves to be appropriate .

5.2 Storage design

5.2.1 General interim waste storage facility requirements

To design the storage for the examined waste, the requirements for the waste or waste fractions to be stored were defined first. Where known, the future probable method to be used to recover the waste was taken as the basis and realistic and appropriate pretreatment of the waste type and scope from today's view were defined.

In the case of the waste streams considered, storage on suitable premises might be required to create the possibility of targeted, individual and allocatable storage and retrieval of partial quantities of the stored material, to protect the material from harmful environmental effects, and also to secure the value, that exists in addition to the pure material value in the effort (e.g. working hours) invested to separate the material.

Basically, requirements for interim storage have to be considered, which will not be fully applicable to each waste. In particular, the requirements of the Landfill Ordinance for long-term storage facilities as well as the information of the German Social Accident Insurance Institution ("Berufsgenossenschaft") for the raw materials and chemical industry (M 062 Storage of hazardous substances), the Federal Institute for Occupational Safety and Health (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin) (TRGS 509,TRGS 510, TRGS 520), the Social Accident Insurance Institution for the timber and metal industry (BGI 582) and the Umbrella Organisation of the German Statutory Accident Insurance Institutions (Deutsche Gesetzliche Unfallversicherung) (BGI/GUV-I 5166) were evaluated. The specific storage requirements for the waste streams considered were then each additionally worked up.

In principle. a storage facility is divided into the following areas: Traffic area, transfer area, storage area, hygiene, social and occupancy areas.

5.2.2 Requirements for waste to be stored and interim storage

5.2.2.1 Interim storage of NdFeB magnets

The total rare-earth metal content of the magnets is mainly similar across the waste streams. Differences exist, above all, in the fractions of the different rare earth metals (primarily neodymium, dysprosium, praseodymium). These can also fluctuate highly in a waste stream. However, the magnets do not differ with regard to the behaviour of their materials. Apart from the form of storage, the design of the interim storage is identical for the different waste streams.

Table 9: NdFeB magnets requirements for interim storage and the interim storage facility requirements

	Requirements
Initial object	• Magnets from hard drives, from head phones and loudspeakers, from hub dynamos, from motors of electric bicycles, from small e-motors from cars, from electric vehicles (drive), from industrial motors, from wind turbines, from air-conditioning systems, from medical equipment (MRT)
Degree of separation	• Magnets or crushed magnetic scrap
Storage form	• In containers (large magnets on pallets)
Materials, components to be removed before placing in storage	• Encasings made of plastic/metal if possible
Pollutants to be removed before placing in storage	• None
Minimum concentration	• 50-100 % magnet fraction in waste to be placed in storage, significantly less if rotors placed in storage
Condition when placed in storage	• Mass: 2 g up to several hundred kg • Size: 0.25 cm³ up to 2-3 m wide for large flat magnet form (often bent) • Conditioning: demagnetised or in shielded containers
Properties	• Hazard potential: low • Material behaviour: corrosion probable (depending on coating); brittle • No known pollutants
Quality requirements	• Only NdFeB magnets, if possible with details of magnet type
Classification	• Non-hazardous
Quantity per year	• Approx. 977 t (total quantity of magnetic material generated, mean value from antici-

	pated quantities for 2020 and 2027, without taking into consideration accompanying materials, losses during collection, dismantling, etc.)
Max. tolerable pollutant content and quality requirements of the recovery process	• Unknown (fully developed process not yet available)
Environmental hazard prevention measures	• Store in a dry place protected from the weather • Note and comply with general storage requirements • Do not store together with acids
Type of interim storage	• Closed storage building (protection from the weather)

5.2.2.2 Interim storage of waste containing cerium/lanthanum: Polishing sludge

Table 10: Polishing sludge requirements for interim storage and interim storage facility requirements

	Requirements
Initial object	• Polishing sludge
Degree of separation	• Dewatered (press)
Storage form	• In containers
Materials, components to be removed before placing in storage	• Water
Pollutants to be removed before placing in storage	• None
Minimum concentration	• 5%
Condition when placed in storage	• Physical state: solid • Mass: partly in powder form • Size: partly in powder form • Conditioning: none
Properties	• Hazard potential: low • Material behaviour: unknown • No known pollutants
Quality requirements	• None
Classification	• Generally not hazardous
Quantity per year	• Approx. 400 t polishing sludge (total quantity generated, mean value from anticipated quantities for 2020 and 2027, without taking into consideration losses during collection, treatment, etc.)
Max. tolerable pollutant content and quality requirements of the recovery process	• Unknown (fully developed process not yet available)

Environmental hazard prevention measures	• Store in a dry place protected from the weather • In case of incomplete dewatering, storage in liquid-tight containers (possibly with drain) • Note and comply with general storage requirements
Type of interim storage	• Closed storage building (protection from the weather)

5.2.2.3 Interim storage of waste containing indium: separated glass fraction containing indium

Table 11: Separated glass fraction containing indium, requirements for interim storage and interim storage facility requirements

	Requirements
Initial object	• LCD devices
Degree of separation	• Glass fraction containing indium
Storage form	• In containers
Materials, components to be removed before placing in storage	• Equipment components (housing, stand base, plastics, cables, background lighting, etc.)
Pollutants to be removed before placing in storage	• After removing the equipment components, no
minimum concentration	• Approx. 50 ppm indium
Condition when placed in storage	• Physical state: solid • Mass: approx. 0.06 – 1.8 kg • Size: 100 cm^2 - 10,000 cm^2 • Conditioning: none
Properties	• Hazard potential: low • Material behaviour: unknown • Indium tin oxide causes skin irritation, eye irritation and irritates the respiratory tracts • Can contain toxic substances (As, Sb, Pb, Sr)
Quality requirements	• Unknown (fully developed process not yet available)
Classification	• Generally not hazardous
Quantity per year	• Approx. 200 t (total quantity, 2,070 t LCD layers, glass fraction approx.10 %, without consideration of losses in collection, treatment, etc.)
Max. tolerable pollutant content and quality requirements of the recovery process	• Unknown (fully developed process not yet available)
Environmental hazard prevention measures	• Store in a dry place protected from the weather • Note and comply with general storage re-

	quirements
Type of interim storage	• Closed storage building (protection from the weather)

5.2.2.4 Interim storage of phosphors

Table 12: Phosphors requirements for interim storage and interim storage facility requirements

	Requirements
Initial object	• Phosphors from gas discharge lamps, from LCD devices and from CRT monitors
Degree of separation	• Separated out phosphor powder
Storage form	• In containers
Materials, components to be removed before placing in storage	• Glass, mercury, equipment components
Pollutants to be removed before placing in storage	• Mercury
minimum concentration	• 1 % rare earth metals
Condition when placed in storage	• Physical state: solid • Mass: in powder form • Size: in powder form • Conditioning: none
Properties	• Hazard potential: low • Material behaviour: unknown • No known pollutants
Quality requirements	• Unknown
Classification	• Generally not hazardous
Quantity per year	• 130 t (Total quantity generated, mean value of expected quantity in 2020 and 2027 without considering losses in collection, treatment, etc.)
Max. tolerable pollutant content and quality requirements of the recovery process	• Unknown
Environmental hazard prevention measures	• Store in a dry place protected from the weather • Note and comply with general storage requirements

5.3 Assessment of the options and alternatives to interim storage

5.3.1 Storage and retrieval time schedule

The build-up of quantities in storage will begin with a delay, because it takes time to set up the delivery processes and to acquire the stakeholders to make deliveries to the storage facility. Further delays can be caused by the fact that the material to be stored is not fully available for a long time, for example, due to slowly growing return of dismantling-compatible products.

The stored quantity will grow as long as there are no retrievals from the storage facility, i.e. at least until the startup of the recovery process to be set up. After startup, the development of the quantity calls by the recovery facility or facilities will depend, among other things, on the following factors:

- the terms of sale
- the quality of the material
- the revenue they can achieve for their products produced from the material
- the terms on which they can procure material from other sources
- the quantity of the materials that they can procure from other sources

A recovery facility, which has set up a process, will not be able to claim exclusive right to the material if they did not set up and operate the storage facility on their own responsibility. An important critical question is therefore how supplier and customer markets for the material behave in the initial years of the facility's operation. If these develop well, other purchasers will also be interested in the stored material. These can be other recovery facilities or even traders, who sell on the material, where this selling on can be to customers abroad, to other domestic customers or also the main domestic purchaser.

On the one hand it can therefore be the case that the material is only partly available to the recovery facility, its capacity utilisation thus continues to be at risk. On the other hand, it is possible that the recovery facility does not want to accept the material at all, for example, due to a poor market situation or because its quality requirements are not fulfilled. In this respect, the long-term interim storage initially involves not only an availability risk for the plant operator but also a sales risk for the operator of the long-term interim storage facility. It is conceivable that the plant operator is also the storage facility operator.

Unlike warehouses used for continuous storage and retrieval and which achieve a more or less stable state of equilibrium, the long-term interim storage facility here must be designed for a maximum storage quantity, which it will however probably only achieve for a relatively short period. The maximum storage capacity for the waste considered here will be equal to several years' quantities.

5.3.2 Cost factors of the interim storage

Costs for stockkeeping are divided into storage costs and stock costs.

Storage costs include costs for property and fitout/equipment as well as running costs.

Stock costs result due to tied capital, i.e. monetary values that are stored. So, the stored goods is evaluated at the purchase price plus additional processing costs. This value is then tied in the form of goods for the storage period. In calculation terms, storage is only interesting economically, if the selling price after storage is higher than the purchase price and the difference exceeds the market interest in the same period. Due to the running costs, the imputed stock costs are always higher, which means that the costs of storage must be added to the goods value.

This calculation leads to it being economically rational to invest as little effort as possible in handling the goods before storage. Separation or sorting involves costs, which are then "stored" with an imputed stock value. The stock costs are therefore increased. Pretreatment is only useful if it can reduce the cost of the storage. To perform this calculation rationally on a large industrial scale, the duration of the storage as well as precise information about the storage requirement are decisive variables.

This costs logic only applies to the cases considered here to a limited extent, as the current lack of recovery methods means that the material only becomes usable at all through storage and at the same time, the material value of non-dismounted waste, for example, whole motors, would tie up currently available comparatively high values.

The stockkeeping costs associated with the erection of a long-term interim storage facility cannot be estimated in a grounded way as long as important questions are not clarified. The costs for the following variants therefore differ considerably

- New erected freestanding storage building with outdoor areas, incoming goods department, social rooms, fence, etc.
- New erected storage building in an existing facility, whose offices and social rooms, fencing, personnel, can be used
- Use of storage space in an existing storage building

An indicative estimate of the investment costs for an independent storage facility with 1,000 m^2 storage space, 100m^2 ancillary space (office, social room, sanitary area, storage facilities) and 660 m^2 traffic area (10%) outside produces an amount of approx. one million euros, i.e. without considering follow-up use possibilities with an assumed use period of ten years, at least around 100,000 euros yearly.

The operating costs at least include the following items: Incoming goods incl. input quality control, outgoing goods, external communication, cleaning, heating and ventilation, security and monitoring, maintenance, software, storage containers, accounting and invoicing, other administration and management. Depending on whether the storage facility has its own personnel or is taken care of by personnel with other tasks, depending on the local wage level, and depending on organisation, quality assurance and documentation obligations and other tasks, these costs can differ considerably. An order of magnitude of around € 100,000 annually would probably have to be assumed here.

The total warehousing costs for this notional storage facility would then be at least around € 200,000 annually. However, this value is probably at the lower end of the expected cost corridor. Moreover, substantial additional investment and operating costs can be incurred, which are not considered here.

A decisive cost factor, that is not considered in this estimate, is the costs for processing the materials to be stored, for example, the costs for dismantling the NdFeB magnets to be stored from equipment.

5.4 Basic legal conditions of interim storage

If regulations on extended producer responsibility, e.g. the WEEE Directive and the ElektroG, require the recovery of precious and minor metals in future, the current lack of recovery options means that interim storage will be required, at least for several precious and minor metals.

5.4.1 Amendment of the obligation to provide proof under landfill legislation

Under the current legal situation, the interim storage of waste before further disposal is subject to different waste, immission control and building regulation requirements, which depend on the type and quantity of the waste to be stored temporarily as well as the duration of the interim storage. The interim storage of waste for recovery over a period of more than three years or the long-term storage of waste for disposal over a period of more than one year constitutes a long-term storage as defined in the Landfill Ordinance and requires assured verification of the following proper and harmless recovery or disposal that is compatible with the common good according to Sec. 23 Landfill Ordinance (Deponieverordnung - "**DepV"**). It is not explicitly defined in law how this assured verification is to be provided.

It can be deduced from the legislative history of this provision that the verification can be provided on the basis of a disposal agreement. With this provision, the legislator wanted to ensure that waste is not only accepted in a long-term storage facility, but is subsequently disposed of in the same quantity. Against this background, waste for which verification of the subsequent disposal cannot be provided should be excluded from storage. The legislator wanted to prevent an unlimited exemption option for the storage of waste. Thus, long-term storage should not be used as a loophole, in order to store waste in an uncontrolled way and for an unlimited period. Instead, the further path of the waste should be predetermined at any time along the disposal route. Against this background, high requirements are to be set for the verification obligation under landfill law. The more specific the verification is, the easier it is for authorities to clearly trace the disposal route at any time and the less likely it is that disposal routes are subsequently cancelled without substitution and long-term storage facilities unobtrusively become unlimited storage sites and can cause hazards for humans and the environment.

Furthermore, the system of the Sec. 23 DepV indicates that fulfilment of the verification obligation under landfill law is only possible if specific disposal options are verified and that a reference to disposal facilities under construction or the planning stage is not sufficient. However, it is possible for the legislator to create provisions which exempt from this verification obligation under landfill law, including for the material stream of the waste containing precious and minor metals, which can be modelled on the existing exceptions of Sec. 23 para. 2 or para. 6 DepV.

According to Sec. 23 para. 2 sentence 3 DepV, an exception from the verification obligation under Sec. 23 para. 1 sentence 2 DepV applies to the long-term storage of metallic mercury waste in long-term storage facilities of class III and IV. The background of this provision is that safe disposal routes for mercury waste were still being investigated at the time that the EU Mercury Regulation (EC) No. 1102/2008 ("**QueckVO**") was enacted. A separate application for approval of an exemption from the obligation to provide proof under the landfill legislation by the competent authority is not required. Instead, verification of the subsequent recovery of this metallic mercury waste in long-term storage facilities of class III and IV is already not required by law.

The further exemption from the verification obligation in Sec. 23 para. 6 DepV was recast as part of the Ordinance on the Reform of Sewage Sludge Recovery (Verordnung zur Neuordnung der Klärschlammverwertung) of 27.09.2017. Further, an exemption from the verification obligation under landfill law can be approved on request for ash from sewage sludge incineration. This option was previously limited to ash from sewage sludge mono-incineration, which was stored in a long-term storage facility, not jointly and without mixing with other waste, for the purpose of recovery of the phosphorus at a later date. The exception now extends to ash from sewage sludge incineration and from sewage sludge co-incineration as well as to residues containing carbon from the pretreatment of sewage sludge through comparable thermal methods, which are stored in a long-term storage facility, not jointly and without mixing with other waste, for the purpose of recovery of the phosphorus at a later date. The long-term storage should be possible even if a final disposal route cannot yet be verified when accepting the waste. Instead it must be certain that this ash and these residues are in principle only to be used for technical phosphorous recovery and a verification cannot be provided, because the relevant plants are still in development or have yet to be established on the market. An exception for storage can also be issued beyond 30.06.2023 since the recasting of the DepV as part of the Ordinance on the Reform of Sewage Sludge Recovery of 27.09.2017. This end date, which was previously contained in theDepV was deleted without substitution. The legislator explains the possibility of long-term storage of sewage sludge (co) incineration ash in that the required recovery plants are currently not yet available in the necessary large industrial scale and therefore recovery is (not yet) economically worthwhile.

Against this background, different options are available to the national legislator.

A first option of the legislator - based on the existing exception of Sec. 23 para. 2 DepV for the temporary storage of metallic mercury waste - consists of creating a further legal exemption from the verification obligation (under landfill law) in Sec. 23 DepV. Insofar as this applies automatically under the DepV, no further exemption decision of the competent authority is necessary. The advantage of such a solution is that no significant additional administrative workload occurs.

Another option of the legislator - based on the existing exception of Sec. 23 para. 6 DepV for sewage sludge(co)incineration ash or, as provided for in the original draft of Sec. 25 DepV in its previous version of 2002 for waste for recovery - consists of adding a new possibility for authorities to exempt from the verification obligation under landfill law upon request for waste containing precious and minor metals to Sec. 23 DepV. In this case, the competent authority could permit an exemption from the obligation to provide proof under landfill legislation on application. Such a preliminary control by the authorities – unlike the automatic legal exception – would have the advantage of increased transparency and would simplify monitoring of subsequent disposal for the authorities.

In both variants, it may be useful to limit the exception period, possibly with a renewal option. Both variants are in conformity with the Landfill Directive, Waste Directive and the German KrWG, in particular, as they serve to secure the priority of recovery, because only with their help a recovery of waste containing precious and minor metals can be secured in a planned but not yet erected waste recovery facility.

In both variants it is also possible for the legal obligation to verify a proper disposal option to be maintained and the storage operator is merely exempted from the obligation to verify proper recovery. In this way, at the start of the storage, the operator would continue to be obliged to verify at least a (subsidiary) disposal route that is compatible with the common good, which can be used in case the planned recovery should fail. Even if recovery plants are actually not built and/or are not available for other reasons, the subsequent disposal route would at least be secured in this way.

5.4.2 No application of the ElektroG to the interim storage of removed components containing precious or minor metals

The interim storage of removed components containing precious or minor metals is not covered by the provisions of the ElektroG for the following reasons. Sec. 20 para. 2 sentence 4, Annex 5 No. 1 ElektroG defines technical requirements for sites for the storage (including temporary storage) of WEEE prior to its treatment, which are to be taken into consideration when approving short and long-term storage facilities. However, it must be noted that the wording of the obligation of Sec. 20 para. 2 sentence 4, Annex 5 No. 1 ElektroG only refers to "waste equipment" and not additional "components" of waste equipment. This already contradicts extending these requirements to components removed from waste equipment. Systematic deliberations confirm this, as other provisions of the ElektroG explicitly refer to the components of waste equipment,

> cf. Sec. 16 para. 2 ElektroG, Sec. 20 para. 1 sentence 1, Sec. 22 para. 3 sentence 1 ElektroG.

Further, this is in conformity with Annex VIII of the WEEE Directive, which also only refers to waste electrical and electronic equipment. Finally, the requirements of the DepV and the relevant immission control or waste legislation for the interim storage of these removed components ensure that health and environment are adequately protected.

5.4.3 Liability of the long-term storage operator

The operators of a long-term storage facility are subject to the operator obligations under immission control law and the obligations of a waste holder, which result from public law (in particular waste law), civil, penal and administrative offences law.

Neither the Federal Immission Control Act (Bundes-Immissionsschutzgesetz "**BImSchG"**) nor the Circular Economy Act (Kreislaufwirtschaftsgesetz - "„**KrWG"**) or the Landfill Ordinance (DepV) define the term for the operator of a long-term storage facility. Therefore, the general definition of an operator given in the BImSchG is to be used. Accordingly, a plant operator is the natural person or corporate entity, who uses the permit and has determining influence on the location, nature and operation of a facility. This regularly applies to those who use the plant on their own account and on their own responsibility and who exercise the actual and legal power of control on their own responsibility. In contrast, it does not matter who is the owner of the plant or to whom the permit was issued. If a legal entity of private or public law exercises this determining influence, this legal entity is the plant operator, not the managing director, the management board or any other body of the legal entity. The legislator assumes that long-term storage facilities can be operated by a public agency, a facility or entity run on its own account by a public agency, a special purpose association or a public law institution. It can also be operated within the scope of a public-private partnership ("PPP"), which exists, for example, for the operation of motorways and for tolling.

In particular, under the waste law, the operator of a long-term storage facility is responsible for the recovery or disposal of the waste and must comply with the existing waste legislation requirements, in particular the priority of recovery over disposal, the requirement for choosing the most high-ranking recovery as possible, existing requirements to keep separate as well as the requirement for proper and harmless recovery in compliance with the public-law regulations. This responsibility under waste legislation continues to exist in accordance with Sec. 22 sentence 2 KrWG until the final and proper completion of the disposal itself, even if the original waste producer or the long-term storage operator entrusts a third party with further disposal of the waste and relinquishes possession of the waste. The completion of the disposal is either the successful completion of a proper recovery or disposal process according to Sec. 7, 15 KrWG or the occurrence of the end of the waste characteristic, after passing through a recovery process in accordance with Sec. 5 KrWG.

5.4.4 Interim storage of minor metals (from waste) for reasons of securing raw materials by economic operators or the state

If the aim is to establishan obligation for economic operators to store waste containing precious and minor metals, this requires a corresponding special justification, in particular, due to the associated infringements of fundamental rights of the companies concerned. In addition, the obligation to stockpile must comply with the principle of proportionality, i.e. be suitable for the pursued purpose (securing supply of certain precious and minor metals), required and reasonable.

The stockpiling and contribution obligations of the Petroleum Stockpiling Act (Erdölbevorratungsgesetz "**ErdölBevG**") can be used as a comparison. According to Sec. 1, 3 ErdölBevG, the Petroleum Stockpiling Association (Erdölbevorratungsverband - "**EBV"**) must keep petroleum stocks that cover 90 days' requirements. The EBV is organised as a public agency of the German federal government with full legal capacity. The Petroleum Stockpiling Association is funded by the contributions of its members. According to Sec. 13 para. 1 ErdölBevG, the members of the EBV are anyone who is domiciled in the European Union, the Swiss Confederation or the Kingdom of Norway and commercially or within the scope of commercial enterprises, imports petroleum-based petrol, diesel fuel, extra light heating oil or aviation turbine fuel into the scope of ErdölBevG or produces it there on their own account or has it produced, insofar as the imported or produced total quantity is at least 25 tonnes per calendar year.

The organisation of petroleum stockpiling by means of a public agency was chosen as a compromise between a pure governmental and purely private solution. The previously planned stockpiling obligation of the companies was abolished to avoid competition problems; a purely governmental solution was rejected, among other things because the hedging of the risks should remain with industry.

Securing the supply of petroleum and petroleum products was classified as a public task by a court and the stockpiling obligation of the ErdölBevG was judged to be lawful because, due to the increasing dependency of the German energy supply on imports, even temporary interruptions of certain import streams can cause serious economic disruptions and continuous minimum stocks of the most important petroleum products are indispensable to bridge possible short-term supply difficulties. For this reason, constitutional complaints of obligated companies were largely unfounded. However, it seems at least dubious that this can equally be transferred to an obligation to stockpile waste containing precious and minor metals.

Further, the obligation to stock waste containing precious and minor metals must be coherent with the raw material strategy of the Federal Government and the European Raw Materials Strategy. According to the current raw material strategy, the Federal Government rejects the stockpiling of industrial raw materials by the state. Instead, it should in principle be a task of the business undertakings to secure their raw material supply. The state activities at federal level are instead concentrated on firmly and efficiently supporting the efforts of industry to secure raw materials, e.g. through support instruments for raw material policies, research funding as well as a coherent raw materials foreign policy.

The European Commission also does not plan to set up an EU-wide stockpiling system for raw materials, although various concepts and procedures for stockpiling have already been analysed, among other things the EU stockpiling programme for crude oil. Here it was highlighted that stockpiling can only solve problems in the short-term; long-term raw material supply shortages on the other hand require structural solutions (substitution, recycling, domestic production). Further, the lack of adequate flexibility of stockpiling obligations was referred to, as it would not be possible to adjust the volumes quickly and the implementation costs would be considerable. Further, the European Commission highlighted that stockpiling required precise knowledge of the supply chains and applications as well as the processing plants of each raw material. An obligation to stockpile certain precious and minor metals would therefore require a change in the European and German raw materials strategy.

5.4.5 Organisation of the long-term storage

A long-term storage facility can be operated by private providers as well as by providers under public law or jointly. If a long-term storage facility were to be operated by a private operator (e.g. the company that subsequently carries out the recovery), it could agree fees with the suppliers. If the long-term storage facility were to be operated as a public facility, user charges, for example, could be levied as consideration for the use according to the law applicable for the respective public facility.

An example of a funding model based on waste charges is the funding of the Association for Land Recycling and Contamination Remediation (Verband für Flächenrecycling und Altlastensanierung - "**AAV"**). Its tasks under Sec. 2 para. 1 Contaminated Site Remediation and Contamination Treatment Association Act (Altlastensanierungs- und Altlastenaufbereitungsverbandsgesetz "**AAVG"**), include remediation investigation and planning and remediation of contaminated sites or harmful soil changes according to the provisions of the Federal Soil Protection Act (Bundes-Bodenschutzgesetz "**BBodSchG**") including the related measures to be undertaken and land recycling, in order to reactivate brownfield sites and contaminated sites for new use and thus to reduce the use of semi-natural and agricultural land.

The AAV is a public corporation for the territory of North Rhine Westphalia. According to Sec. 6 para. 1 AAVG, its members are the North-Rhine Westphalian districts and independent towns and cities and the state of North-Rhine Westphalia. In addition, there are voluntary members of the association according to Sec. 6 para. 2 AAVG. These are all natural persons and legal entities under private and public law as well as their associations, who have undertaken to make voluntary contributions to the association. The AAV receives contributions and earmarked funds from its members to fulfil its tasks. The contribution obligations of the districts and independent towns and cities and the state of North-Rhine Westphalia are public charges. The contributions are attributable costs in the calculation of the use charges by the public-law waste management company (Sec. 9 para. 2 sentence 2 State Waste Act (Landesabfallgesetz) NRW). However, the argument against a legal waste charge solution, in particular, is that - as long as manufacturers and distributors of the products containing precious and minor metals are not involved in the costs for the storage – they also have no incentive to participate in the development of recovery techniques and to design and label their products so that prompt recovery is enabled.

Funding via a manufacturers’ fund, as discussedwithin the legislative procedure of the AltfahrzeugV and already implemented within the scope of the disposal of radioactive waste, is conceivable in principle, but is not expedient for waste containing precious and minor metals for the following reasons. Within the scope of the AltfahrzeugV, for competition and cartel reasons, the legislator already preferred a decentralised obligation of the manufacturers rather than a manufacturers’ fund and further pointed out that a monopoly-like fund structure would not promote competition for innovative recycling techniques but instead restricted the freedom of the market players. The differences to the fund solution within the scope of the disposal of radioactive waste should also be pointed out. The fund provided for there can be justified by the special features of nuclear disposal legislation, in particular the particular hazard situation posed by the disposal of radioactive waste. A comparable hazard is not caused by the long-term storage facilities of waste containing precious and minor metals.

A legally conceivable solution would also be for the manufacturers and distributors of products containing precious and minor metals to bear the costs, which could be stipulated in a new ordinance to be issued under Sec. 25 KrWG as implementing extended producer responsibility. In addition to labelling, collection, take-back, recovery obligations and obligations to provide dismantling information, such a regulation could also include obligations of actors or persons responsible for products to bear financial responsibility, however, these obligations would have to comply with the principle of proportionality and be carefully coordinated with existing provisions regarding extended producer responsibility (e.g. ElektroG, AltfahrzeugV).

6 Environmentally optimum recovery yield of precious and minor metals

Based on a scientific consideration, criteria for estimating an environmentally optimum recovery yield should be derived and exemplarily applied to selected waste streams containing precious and minor metals. In this way, a basis should be created to enable requirements for the recovery yields to be achieved to be proposed for consideration in legal instruments of the circular economy.

The recovery yield itself is the product of a sequence of yields along the steps of the recycling chain, from the collection of the waste products to the pretreatment (e.g. dismantling) and treatment to separate complex fractions through to recovery, i.e. the recovery of marketable target metals or target metal compounds.

6.1 Environmental cost assessment

A large number of influencing factors must be taken into account in the estimation of the environmental cost. Within the scope of this project, ways of producing a rough estimate only can be developed, especially as the tool to be developed should be able to be used with reasonable effort.

Detailed quantitative analyses not only require more detailed investigations, e.g. life-cycle assessments, but also they are only possible in relation to the specific methods used for the recovery, most of which are currently unknown.

Even if the consistent definition of the criteria and assessment standards for a benefit analysis requires a large effort, it seems most suitable because several parameters can be merged but they do not necessarily have to be quantified. The method can be applied to different treatment and recovery processes and from experience, is especially suitable for decision-making considerations in case of target conflicts.

Table 13 uses a notional example to show that the recovery yield is ultimately a sequence of yields along the recycling chain.

Table 13: Yields of notional ACTUAL process chains (Case A - D)

Process steps in the recycling chain	Case A	Case B	Case C	Case D
Collection	0%	50%	50%	50%
Preparation/pretreatment	0%	90%	50%	50%
Recovery	90%	95%	95%	0%
Total yield	**0%**	**43%**	**24%**	**0%**

This clearly shows that it is not useful to consider the target variable recovery yield generally. Instead, the parameters should be identified and analysed, which most influence the individual yields of the process steps along the recycling chain.

Criteria for benefit analysis

Table 14 shows a selection of factors, which could describe the indicators of a benefit analysis based on the task in this project.

Table 14: Exemplary factors, which can describe the indicators of a benefit analysis

Indicators	Factors
Ecology: GWP (including ADP, CTU[1]), etc.)	Transport movement to the pretreatment, treatment and recovery (debit)
	Energy for pretreatment, treatment and recovery (debit)
	Substances/materials for pretreatment, treatment and recovery (debit)
	System benefit for substituted primary material (credit)
Criticality	Supply risk
	Vulnerability
Technical aspects	Effort for removing residual and hazardous materials after pretreatment, treatment and recovery
	Effort for emission reduction measures (air/water) during treatment and recovery
	Effort for further processing of output fractions from the recovery
	Yield of non-target materials (compared to the actual situation) with recovery
Economy: Costs (as indicator for the economic expenditure)	Collection process costs (debit)
	Pretreatment process costs (debit)
	Treatment process costs (debit)
	Recovery process costs (debit)
	Financial benefit from the marketing of the recycled material (credit)

[1] GWP = Global Warming Potential = Carbon Footprint
ADP = Abiotic Depletion Potential = Depletion of mineral, fossil and renewable resources
CTU = Comparative Toxic Unit for Humans = Human toxicity

In principle, it is possible to use the factors from Table 14 for each waste stream, to quantify each metal as well as each step of each recycling chain and to calculate indicators using the ratios of cost (debit/burden) and benefit (credit/relief):

$$Indicator = \sum Effort\ (burdens) - \sum Benefit\ (credits)$$

Weighting and merging of the indicators, e.g. using the benefit analysis method, would lead to a utility value for the treatment and recovery processes. However, this utility value provides little information about the optimum recovery yield, as most parameters – if at all – are each only based on one individual value for the yield of a treatment and recovery process already in use (ACTUAL situation).

Closer consideration shows that, due to the very complex relationships, a great deal of effort would be required to determine real factors depending on different yields (= recovery yields). The dependency of the factors - and thus the indicators – on the recovery yields can assume the entire range from linear to highly exponential.

All functions, which describe the dependencies of the indicators on the recovery yield - whether determined mathematically (e.g. $y = x^2$) or estimated on the basis of empirical values (e.g. for recovery yields from 0% to 50% each doubling the emissions per 10% rise, then increase in emissions to the 2.2-fold to 4-fold per 10% rise), require a base value. In this study, this could be a cost, emission, expenditure or target variable value for a known yield of a treatment and recovery process already in use (ACTUAL situation), or - if no process has been technically implemented yet - it could be an estimate. The base values for the yields of non-target materials could be taken from research results or could be estimated based on these. The process costs could also be roughly approximated to realistic orders of magnitude, assessed qualitatively and offset against primary metal prices values to obtain total costs.

Merging the dependencies of the indicators on the recovery yield that could possibly be determined in this way in a tool is nevertheless a large challenge. A feasible solution would be to set up a matrix in which the purely qualitative effort and emission increases with increasing recovery yield (or even effort and emission reductions) are calculated on the basis of the starting values as well as functions to be estimated. For the interpretation of the results, a graphic representation in the form of regression curves could be possible, which are averaged from the specific load curves of the process steps.

However, the risk of such an approach is that despite immense data and calculation requirements and a large effort to apply it to each specific issue, less reliable results are achieved, which only simulate accuracy.

For this reason the procedure outlined in the following section was chosen instead, i.e. identify and analyse the qualitative or semi-quantitative parameters for increasing the recovery yield with regard to their environmental effectiveness and efficiency.

6.2 Routes to optimum recovery yield – the assessment method

6.2.1 Preliminary remarks

Due to the poor realisability of determining an environmentally optimum recovery yield as described above, the following method is used to provide a tool that enables the estimating and classification of that which is realistically doable. To this end, measures for increasing the recovery yield were identified and assessed qualitatively to semi-quantitatively with regard to their environmental efficacy and efficiency in a spreadsheet tool.

In addition to the criteria used in the tool, other criteria can also be important for the assessment of measures to increase the yield of precious and minor metals, for example:

Chemical bonding form: The chemical bonding form in which the metals to be recovered exist is important for the environmental and economic treatment cost. This aspect is also implicitly input into the assessment by the tool, as treatment processes for metals that exist in oxidic form are generally more complex than those for metals in their elementary form. As a result, on the one hand further process steps will be required, which are associated with additional yield losses. On the other hand, the then more complex processes must also be assessed differently, as they cause greater environmental burdens and costs.

Mining - main and byproducts: Whether and to what extent measures to increase the recovery of metals are environmentally purposeful, also depends on the market situation of such metals. For example, the rare earth metals cerium and lanthanum occur in relatively large quantity in the primary extraction of other rare earth metals. Availability bottlenecks are therefore hardly to be expected. Cerium or lanthanum acquired from recycling would therefore hardly displace material that comes from mining. This factor is however also implicitly represented by the tool because it is reflected in the comparatively low market prices of cerium and lanthanum, which are significantly below those of other rare earth metals. Moreover, the greenhouse gas emissions of the extraction of lanthanum and in particular cerium are also comparatively low.

This tool offers a pragmatic approach for transparent approximation of a realistically achievable recovery yield. It allows estimation of the effectiveness of the measures considered as well as their qualitative assessment.

The listed assessments and yield increases – also in the application examples described in the following - are generally assumptions, which are based on bifa experts' estimates. These are not scientifically substantiated figures, but instead approximations of the reality to be expected. Depending on the arrangement of the measure, different values could be more realistic. For example, the yield achieved with the crushing of components and the manual sorting out of printed circuit board fragments with greater effort also leads to better results and with less effort to poorer results. The values used are the result of the most realistic estimate possible.

An important benefit of the tool is the possibility to play with potential measures and their assessments, without great effort, in order to better judge their effects. It does not claim to replace detailed analyses, practical tests and life cycle assessments. These remain indispensable when reliable quantitative assessments are required. In case of a poor database, this tool also offers the option of estimating currently existing recovery yields as well as realistically expected recovery yields and to assess the effectiveness of potential measures. The tool operates with easy to handle assessment criteria. How to handle it, can be learned quickly.

6.2.2 Classification of potential measures

Measures to improve the recovery yield of an initial situation on the one hand include direct measures, which directly contribute to improving a process, and on the other hand, overarching legal, organisational and technical control measures[6].

General catalogue of direct potential measures: Variations and examples

For the classification of potential measures, a package of measures has been drawn up, which is intended to assist with the characterisation of the potential measures with regard to ecology, energy demand, costs and feasibility with an initial assessment (default assessment). The package of measures includes seven categories with a total of 20 variants, which can help to improve a process and have a noteworthy environmental, energy or cost effect.

Overarching control measures: Examples

Overarching control measures leading to an improvement either have no noteworthy direct environmental effects themselves or their possible effects cannot be evaluated here. But like the general direct measures listed to date, they can also be assessed with regard to the efficacy using the tool.

6.2.3 Qualitative assessment of the proposed measures: Criteria and attribute characteristics

The proposed measures are assessed qualitatively or semi-qualitatively on the basis of the following criteria:

- Global Warming Potential (GWP): Level of impact on the environment due to greenhouse gases

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6 The possible side-effects of overarching control measures on factors, such as the quality of the collected waste, costs or the willingness of stakeholders to participate with their consequential environmental effects cannot be analysed in detail here.

- Cumulated Energy Demand (CED): Level of consumption of fossil fuels and renewable energy sources
- Toxicology: Level of human and/or ecotoxic contamination of soil and waters
- Influence on the yield of valuable non-target materials: Comparison with the initial situation
- Realisation opportunities: technical development status of the measure or prospects for success of the implementation
- Realisation effort: Costs of implementation

Suggestions for a fundamental basic assessment of the variants in the general package of measures are presented in the following. These values should offer possible assessments, which may have to be deviated from in an individual case.

Organisational measures

GWP and CED as well as the costs of realising measures are essentially determined by the number of transport movements as well as the transport distances, insofar as changes result here. The production and maintenance of the vehicles are themselves not considered as environmental impact.

It is assumed that the losses in non-target materials are reduced by implementing organisational measures while no toxicologically relevant emissions are to be expected. The realisation opportunities for the implementation of optimisation measures must be estimated specifically based on the range of measures. The realisation chances for introducing new collection systems are assessed to be rather poor.

Manual processes

The GWP and CED for manual processes are essentially determined by the building heating. If applicable, a (small) power consumption is to be taken into account for tools used. In contrast, the provision of human work is not considered as environmental impact.

It is assumed that for the realisation effort, a wide range exists between low costs for optimisation/intensification measures and high costs for new or additional more time-consuming/labour intensive manual processes. Toxicologically relevant emissions are not to be expected. Effects on the loss of non-target materials and the realisation prospects must be estimated specifically for each measure.

Mechanical processes

GWP and CED for mechanical processes are essentially determined from the energy consumption for the machines and plants used. The production and maintenance of the machines and plants themselves are not considered as environmental impact.

It is assumed that the realisation effort lies between very low costs for optimisation/intensification measures and high costs for new or additional more complex mechanical processes. Toxicologically relevant emissions are not to be expected. Effects on the loss of non-target materials must be estimated specifically for each measure, as well as the realisation effort. High costs at least must be expected only for new or additional more complex mechanical processes.

Hydrometallurgical processes

The GWP and CED for hydrometallurgical processes are essentially determined by the energy consumption. The costs for the realisation of a measure also influence the energy consumption, however the quantity of auxiliary materials used also play a decisive role here. These use quantities can also be responsible for toxicologically relevant emissions that occur. The production and maintenance of the plants and plant technology themselves are not considered as environmental impact.

Effects on the loss of non-target materials and the realisation prospects must be estimated specifically for each measure.

Pyrometallurgical processes

GWP and CED and the costs for the realisation of measures for pyrometallurgical processes are essentially determined by the demand for energy sources for thermal energy. The production and maintenance of the plants and plant technology themselves are not considered as environmental impact.

Toxicologically relevant emissions are to be expected to a small extent only and effects on the loss of non-target materials and the realisation prospects must be estimated specifically for each measure.

High-temperature processes (temperatures > 600 °C)

GWP and CED as well as the costs for the realisation of measures for high-temperature processes are essentially determined by the demand for energy sources for thermal energy. The production and maintenance of the plants and plant technology themselves are not considered as environmental impact.

Toxicologically relevant emissions are only to be expected to a small extent. Effects on the loss of non-target materials must be estimated specifically for each measure, as well as the realisation effort. Very high costs must be expected only for new or additional more complex high-temperature processes.

Low temperature processes (temperatures < 400 °C)

GWP and CED for low-temperature processes are also essentially determined by the demand for thermal energy, even if the processes operate at lower temperatures than high-temperature processes. The largest cost aspect is the plant technology necessary to implement a measure.

Toxicologically relevant emissions are to be expected to a small extent only and effects on the loss of non-target materials and the realisation prospects must be estimated specifically for each measure.

6.2.4 Initial data for quantitative assessment of the determined recovery yields

In an overall assessment of the selected measures, the avoidable greenhouse effect emissions, the avoidable consumption of fossil fuels and renewable energy sources as well as the avoidable costs for the purchase of primary raw materials are determined. These are based on

- the global warming potential of the substituted target elements in the global market mix,
- the cumulated energy demand for the substituted target elements in the global market mix as well as
- primary metal prices of the substituted target elements.

6.2.5 Presentation of how the spreadsheet tool works using the example of a waste stream with one partial quantity (printed circuit boards containing precious metals taken from end-of-life vehicles)

The outlined procedure for estimating the optimum recovery yield with the help of the spreadsheet tool is illustrated in the following using the example waste stream containing precious metals of the *printed circuit boards taken from end-of-life vehicles*.

Definition of the initial situation for the different waste streams

The total number of end-of-life vehicles that occur in Germany annually is not known and can only be roughly estimated. In this example, 1 million vehicles/a is assumed.

The total quantity of printed circuit boards contained is estimated at 1,000 t/a with a rising trend for future quantities with simultaneous falling precious metal content. The target metal content of the printed circuit boards is assumed as follows:

- 0.016 % wt gold
- 0.061 % wt silver
- < 0.01 % wt palladium
- < 0.001 % wt platinum

Based on the primary metal prices of the target materials, the potential value of the total quantity of end-of-life vehicles is estimated to be approx. € 9.55m. However, due to the current almost completely lacking separation of vehicle electronics and material losses along the recovery chain, only part of this potential can be used. On the other hand, the theoretical total potential is larger, because only part of the end-of-life vehicles in Germany are recovered. The collection is therefore incomplete.

With the substitution of equivalent primary raw material quantities in the global market mix, the recovered quantities of target materials can theoretically avoid greenhouse effect emissions of approx. 3.84m kg CO_2 equivalents as well as the consumption of fossil fuels and renewable energy sources of approx. 56m MJ. As described above, this potential is currently not used.

Breakdown of the initial process into process steps

For the treatment of the *printed circuit boards taken from end-of-life vehicles* waste stream, the process chain was divided into the four process steps: collection (take-back of vehicles), preseparation (localisation of control devices/electronic components worth removing and removal of the vehicle electronic components), treatment (breaking open the housing and sorting out the printed circuit boards and printed circuit board fragments) and recovery (further processing to produce target metals).

Definition of the initial situation

As reliable information could not be researched, for the <u>collection</u> process step it was assumed that by using existing collection structures for end-of-life vehicles, half the assumed total quantity of end-of-life vehicles occurring, i.e. 500,000 vehicles, are collected and dismantled.

At present the dismantling and recycling of printed circuit boards from vehicle electronics takes place to only a small extent, above all to obtain spare parts. Therefore, it is approximately assumed that the yield of printed circuit boards from end-of-life vehicles, which are fed into the <u>preseparation</u> is 0 %. The yield of the initial situation in the <u>treatment</u> process step is therefore also 0 %.

Separated printed circuit boards are sent to copper smelters to recover the target metals and other metals, in particular copper. The recovery processes operated there generate metal recycling rates > 95 % for the target materials gold, silver, platinum and palladium. For this reason, the yield of the initial situation in the <u>recovery</u> process step is set to 95 %.

Collection of potential measures for improving the initial situation and specification

The following potential measures and improvement approaches have been identified to increase the yield of the initial situation:

<u>Collection</u>: **(E1)** Increase in the efficiency of the collection structures by adjusting opening hours, advertising, employee training, information in the workplace, etc.

(E2) More drop-off points

<u>Preseparation</u>: **(V1)** Introduction, expansion and optimisation of manual dismantling of electronic components

(V2) Removal of easy to localise electronic components as part of existing dismantling processes

(V3) Employee strengthening through training and visualisation of the relevant electronics components in the end-of-life vehicle

Treatment: **(A1)** Separation of the printed circuit boards from the separated vehicle electronics components via housing opening by means of an impact mill and subsequent sorting out of the printed circuit boards and printed circuit board fragments

(A2) Automatic sorting lines for separating out small printed circuit board fragments

(A3) Extraction of a metal fraction containing precious metal from filter dust produced

Recovery: NONE → The recovery processes in a copper mill are today's technical standard and are well optimised throughout. Metal recycling rates of > 95 % for the target materials are the best available techniques and can hardly be increased.

Estimation of the improvement in the yield of the process step starting from the initial situation

Table 15 summarises the estimates for the increases in the yield of the initial situation on implementing the potential measures/improvement approaches.

Table 15: Estimation of the effect on the yield of the initial situation caused by implementation of the potential measures

Process step	Potential measure/improvement approach	Effect on the yield of the initial situation
Collection	**(E1)** Increase in the efficiency of the collection structures by adjusting opening hours, advertising, employee training, information in the workplace, etc.	+ 2 %
	(E2) More drop-off points	+1 %
Preseparation	**(V1)** Introduction, expansion and optimisation of manual dismantling of electronic components	+ 40 %[1]
	(V2) Removal of easy to localise electronic components as part of existing dismantling processes	+ 20 %[1]
	(V3) Employee strengthening through training and visualisation of the relevant electronics components in the end-of-life vehicle	+ 10 %[1]
Treatment	**(A1)** Separation of the printed circuit boards from the separated vehicle electronics components via housing opening by means of an impact mill and subsequent sorting out of the printed circuit boards and printed circuit board fragments	+ 30 %[2]
	(A2) Automatic sorting lines for separating out small printed circuit board fragments	+ 10 %[1]
	(A3) Extraction of a metal fraction containing precision metal from filter dust produced	+ 1 %[1]

1 Assumption
2 Schüler et al. 2017; p. 21/26

Qualitative assessment of the selected measures

In this step the measures and improvement measures are assigned to a variant of the general package of measures (cf. section 6.2.3). Thus a qualitative basic assessment (default values) takes place with regard to the six criteria presented. If it was not possible to assign a default value to a criterion, this is identified and a specific estimate is necessary. In addition, if necessary, all predefined default values of the criteria can be changed within the attribute characteristics.

Determination of the yield of the recycling process after implementing selected measures

In the first step - in line with the procedure for a benefit analysis - the importance (weighting) of a criterion is separated from its assessment (attribute characteristic). To do this, it is first defined which relative importance is attributed to the criteria.

In the second step an assessment is made of each measure and each criterion separately. Firstly, separate intermediate values are calculated, by multiplying the expected yield of a measure by each attribute characteristic of the criteria:

$$Interim\ value_i = Yield \times Characteristic_i$$

Then the intermediate values are multiplied by the weighting factors and through the summation of all criteria for each measure a value of benefit is calculated, with which the respective measure is assessed:

$$Value\ of\ benefit = \sum_{i=6} Interim\ value_i \times Weighting_i$$

In the third step, a measure is selected for each process step. To determine the optimum recovery yield, in general, these will be the measures with the best measure assessment. In this example, these are:

Collection:	**(E1)** Increase in the efficiency of the collection structures by adjusting opening hours, advertising, employee training, information in the workplace, etc.
Preseparation:	**(V1)** Introduction, expansion and optimisation of manual dismantling of electronic components
Treatment:	**(A1)** Separation of the printed circuit boards from the separated vehicle electronics components via housing opening by means of an impact mill and subsequent sorting out of the printed circuit boards and printed circuit board fragments

In the fourth step, by multiplying the expected yields of the selected measures in the four process steps, ultimately, the total yield of the recycling process after implementing the selected measures is calculated. On selecting the measures with the best assessment, this is an approximation of an optimum recovery yield.

In this example, these are

- 52 % in the collection process step,
- 40 % in the preseparation process step,
- 30 % in the treatment process step and
- 95 % in the recovery process step.

In total, with the selected measures, the total yield of the recycling process obtained after implementation of the measures is 5.9 %.

Quantification of the system benefit due to the increase in yield achieved

In the final quantification of the gross system benefit due to the increase in yield achieved, the determined total yield of the recycling process is expressed in proportion to the original theoretical potential GWP, CED and primary metal prices value in the waste stream considered.

The target metals obtained with 5.9% yield correspond to

- greenhouse effect emissions of approx. 227,000 kg CO_2 equivalents,
- consumption of fossil fuels and renewable energy sources equal to approx. 3.3m MJ as well as
- costs for purchasing the primary raw materials equal to € 566,000

Table 16 summarises once again the different yields assumed for this waste stream, supplemented by a variant with very optimistically estimated yields.

Table 16: Assumed yields in the waste stream containing precious metals *Printed circuit boards from end-of-life vehicles*

Process step	Initial situation	After implementation of selected measures / improvement approaches	
		with conservatively estimated yields	with very optimistically estimated yields
Collection	50 %	52 %	85 %
Preseparation	0 %	40 %	60 %
Treatment	0 %	30 %	85 %
Recovery	95 %	95 %	96 %
TOTAL	**0 %**	**5.9 %**	**41.6 %**

Table 16 shows that the recovery yield to be expected, even with very optimistically estimated yields in the four process steps over the entire recycling process is significantly below 50 %. The target metals obtained with the determined recovery yield of 41.6% correspond to

- greenhouse effect emissions of approx. 1.6 m kg CO_2 equivalents,
- consumption of fossil fuels and renewable energy sources equal to approx. 23.4m MJ as well as
- costs for purchasing the primary raw materials equal to € 3.97m .

Compared to the results of conservatively estimated yields, this corresponds to a roughly 6-fold improvement in each case.

It becomes clear that due to the multiplying yields over the process steps of the recycling chain, it will be very difficult to achieve high recovery yields. The whole calculation is based on assumptions regarding the expected yields due to the measures/improvement approaches in the four process steps. Although these yields with values of 52 % (collection), 40 % (preseparation), 30 % (treatment) and 95 % (recovery) each lie clearly within the double-digit percentage range, under the described assumptions, a recovery yield of only 5.9 % is determined over the entire recycling process. Even if the actually collected quantity of 1 million end-of-life vehicles is used as the initial quantity, i.e. it is assumed that 100% of the end-of-life vehicles are currently added to the recovery chain, the recovery yield would only be 11.4 %.

6.2.6 Results for a waste stream with several partial quantities (NdFeB magnets)

This waste stream includes several partial quantities, of which the three largest in terms of quantity, namely magnets from industrial motors, magnets from small e-motors from cars as well as magnets from IT (together around 85 % of the total quantities and of the total potential value), are considered in the following.

The total quantity of NdFeB magnets contained in the currently collected partial quantities is estimated to be 402 t/a in total in the year 2020 with future rising trend. The quantity of the partial quantities considered and the assumed target metal content are summarised in Table 17.

Table 17: Quantities generated and composition of the NdFeB magnets considered

Partial quantity	Quantity [t/a]	Dysprosium [% wt.]	Neodymium [% wt.]	Praseodymium [% wt.]
Magnets from industrial motors	60	10	20	-
Magnets from IT	275	2.3	29	-
Magnets from small e-motors from cars	67	1.0	28	1.0

The potential measures separately defined and assessed for each partial stream essentially include improving collection, realising the manual dismantling of components containing NdFeB magnets, manual removal of magnets or in the case of IT, mechanical separation of the magnetic material as well as realisation of the hydrometallurgical treatment to form rare-earth metal oxide concentrates.

Table 18 summarises the yields assumed for the NdFeB magnets waste stream.

Table 18: Assumed yields in the waste stream containing rare earth metals *NdFeB magnets*

Process step	Initial situation			After implementation of selected measures / improvement approaches					
				with conservatively estimated yields			with very optimistically estimated yield		
	IM	IT	AF	IM	IT	AF	IM	IT	AF
Collection	30 %	50 %	50 %	30 %	65 %	52 %	60 %	70 %	85 %
Preseparation	0 %	0 %	0 %	50 %	20 %	30 %	70 %	85 %	80 %
Treatment	0 %	0 %	0 %	50 %	60 %	60 %	85 %	80 %	80 %
Recovery	0 %	0 %	0 %	85 %	85 %	85 %	90 %	90 %	90 %
TOTAL			**0 %**			**6.8 %**			**42.3 %**

IM = magnets from industrial motors
IT = magnets from IT
AF = magnets from small e-motors from cars

In the initial situation for the *NdFeB magnets* waste stream containing rare earth metals it is assumed that the target metals dysprosium, neodymium and praseodymium considered here are currently completely lost during the recycling process chain for end-of-life vehicles. By implementing various measures /improvement approaches in the process steps of the recycling process with rather conservatively estimated yield increases, a recovery yield (total yield) of 6.8 % can be achieved.

Table 18 shows that even with very optimistically estimated yields in the four process steps, a recovery yield of around 42 % only can be achieved over the entire recycling process. The target metal quantities recovered in this way correspond to

- greenhouse effect emissions of approx. 1.6m kg CO_2 equivalents,
- consumption of fossil fuels and renewable energy sources equal to approx. 36.1m MJ as well as
- costs for purchasing the primary raw materials equal to € 4.1m.

Compared to the results of rather conservatively estimated yields, this corresponds to an improvement by more than 6-fold in each case.

7 Measures for increasing recycling of precious and minor metals

The measures developed in the project were qualitatively assessed with a view to increase the recovered quantity of target metals, the degree of obligation, realisation prospects, realisation expense and effects on the recovery of other metals. See chapter 1.5.

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