Zentrum Ressourceneffizienz

Im Auftrag des:

Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz

VDI ZRE publications: Brief analysis no. 33

Resource efficiency due to innovative recycling technologies and processes

© PantherMedia/Romaset (edited)

December 2023

VDI ZRE Brief analysis no. 33: Resource efficiency due to innovative recycling technologies and processes

Author:

Dr.-Ing. Ulrike Lange, VDI Zentrum Ressourceneffizienz

We thank Prof. Dr.-Ing. habil. Christina Dornack, Director of the Institute for Waste and Recycling Management at the Technical University of Dresden, for her professional support.

This brief analysis was developed on behalf of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection.

The brief analyses of the VDI ZRE provide an overview of current developments in the field of resource efficiency in research and industrial practice. They contain a compilation of relevant research results, new technologies and processes as well as best-practice examples. The brief analyses thus provide an introduction to selected resource efficiency topics for a broad audience with business, research and administration background.

Editorial:

VDI Technologiezentrum GmbH
VDI-Platz 1
40468 Düsseldorf

Tel. +49 30-27 59 506-0
zre-info@vdi.de
www.ressource-deutschland.de

Cover: © PantherMedia / Romaset (edited)

Printed on environmentally friendly recycled paper.

VDI ZRE publications:
Brief analysis no. 33

Resource efficiency due to innovative recycling technologies and processes

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
ADR	Agreement concerning the International Carriage of Dangerous Goods by Road
AF	Alternative fuel
AI	Artificial Intelligence
AlMn	Alkaline-manganese
AR	Argon
a-Si	Amorphous silicon
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
CdTe	Cadmium telluride
CIGS	Copper-indium-gallium-diselenide
CIS	Copper-indium-selenium
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalents
c-Si	Crystalline silicon
DIN	Deutsches Institut für Normung e.V.
DIN SPEC	Consortium standard
WEEE	Waste electrical equipment
ETS	Emission Trading System
EuRIC	The European Recycling Industries' Confederation

EVA	Ethylene vinyl acetate
GDSN	Global Data Synchronisation Network
HDPE	High Density Polyethylene
HSI	Hyper-spectral Imaging Technology
LAGA	Federation/Länder Working Group on Waste
LCC	Leaf-Branch Compost Cutinase
LCD	Liquid Crystal Display
LDPE	Low Density Polyethylene
LFP	Lithium iron phosphate
Li-Ion	Lithium ions
LWP	Lightweight packaging
MEG	Mono-ethylene glycol
WIP	Waste incineration plant
NIR	Near-infrared spectroscopy
Ni-Cd	Nickel Cadmium
Ni-Mh	Nickel metal hybrid
NMC	Nickel manganese cobalt
PA	Polyamide
PE	Polyethylene
PERC	Passivated Emitter Rear Cell
PET	Polyethylene terephthalate

PP	Polypropylene
PCC	Paper, cardboard, cartons
PS	Polystyrene
PU	Polyurethane
PV	Photovoltaics
PVC	Polyvinyl chloride
RR	Recycling rate
SKU	Stock Keeping Unit
EEER	Electrical and Electronic Equipment Register
SME	Small and Medium-Sized Businesses
SX	Solvent extraction
t	tonnes
TBS	Tracer Based Sorting
TRL	Technical Readiness Level
UV	Ultraviolet
VDI	Association of German Engineers
VDI ZRE	VDI Zentrum Ressourceneffizienz (Competence Center for Resource Efficiency)
PfRU	Preparation for Reuse
WEEE	Waste electric and electronic equipment
wt.-%	Percent by weight
ZnC	Zinc carbon

PART 1: BRIEF ANALYSIS

1 INTRODUCTION

Resource efficiency makes a major contribution to protecting natural resources. This needs not only selective measures, but also a sustainable and comprehensive transformation of the economy. This is the only way to ensure that sufficient resources will also be available for future generations.

The circular economy concept is the basic cornerstone of this transformation. The circular economy in the broader sense refers to a production and consumption model in which products and materials are managed in the economic cycle for as long as possible. Strategies such as repairing, reusing, reconditioning, recycling and leasing extend and intensify the useful life of products and materials and thus maintain the added value.[1]

Combining ecological requirements with economic development opportunities, innovation and social responsibility is the main idea behind the German resource efficiency programme ProgRess III. For this reason, among other things it specifies programme points to protect natural resources. Alongside responsible raw material supply, these also include products designed with careful stewardship of resources in mind, production with efficient use of resources, sustainable lifestyle and consumption and avoiding and reducing waste quantities and pollutant accumulations. Resource efficiency therefore aims to avoid unnecessary use of materials and energy.[2]

The goal of a resource-efficient circular economy is therefore to minimise the use of raw materials and to reduce material flows to an extent where the planetary limits can be maintained with the current economy. At the same time, this aspiration means using the unavoidable, necessary raw materials for as long as possible and managing them in a largely closed cycle - under the condition that the expense required for this does not exceed the benefit to be derived.

Recycling is the key strategy for managing a circular economy that lies downstream for usage intensification and useful life extension. In Germany, recycling is part of waste management and is described as a recovery method

[1] Cf. Europäisches Parlament (2022).

[2] Cf. Bundesregierung der Bundesrepublik Deutschland (2020).

in the German Circular Economy Act, by means of which waste is processed into products, materials or substances either for the original purpose or for other purposes.[3] The collection, reconditioning and reuse of the secondary raw materials already work very well for conventional raw materials, such as glass or steel. For materials and products such as plastics (cf. Chapter 2), batteries and rechargeable batteries (cf. Chapter 3), waste electrical and electronic equipment or precious and special metals (cf. Chapter 4) or PV modules (cf. Chapter 5), however, further development is needed to establish a resource-efficient circular economy.

In addition to various challenges, such as the stringent quality demands of recyclates or sometimes ambitious and complex regulatory requirements, more efficient technologies for the optimised development of flows of recyclables are needed.[4] For this reason, a great deal of research and development work is currently in progress to tap into successive resource efficiency potentials and further advance the expansion of a resource-saving and resource-efficient circular economy.

This brief analysis provides an insight into the current status of the development of innovative recycling technologies and recovery methods for the above-mentioned fractions[5]. The aim is to give small and medium-sized companies (SMEs), in particular from the manufacturing sector, an insight into the processes and the current opportunities and challenges in the disposal and recycling sector. This aims to advance continuously an increasing understanding across wealth creation stages and a transparent perception of the entire wealth creation chain and subsequently improve a resource-efficient circular economy - involving all participants.

3 Cf. article 3 para. 3 German Circular Economy Act, cf. Bundestag der Bundesrepublik Deutschland (28. Oktober 2020).

4 Cf. Lange, U. (2022).

5 Information on other fractions, such as textiles, glass, metal and paper can be found in the VDI ZRE Material Database: https://www.ressource-deutschland.de/werkzeuge/ ressourceneffizienz-in-der-praxis/materialdatenbank/

2 PLASTICS

2.1 Plastics Market challenges

Plastic recycling is currently in transition. The problems of plastics remaining in nature has led to increased awareness among the public for how to deal with plastics in their everyday dealings. Reports on the littering of the seas, the increasing accumulation of microplastics in nature, people and animals or the amounts of plastics shipped overseas have increased pressure on politics and those involved in the plastics wealth creation chain.

2.1.1 Current Recycling Situation

Recycling rates

Currently, the officially published **recycling rates for all plastic waste** (material recovery from production waste and post-consumer waste) are just under 47 percent (input in first recycling plant, old calculation basis, Table 1) or, using the new calculation method of the EU Implementing Decision 2019/665, **just under 35 percent** (input in the process stage of compounding or processing). The original recycling rate related to the input quantity into the first recycling plant. This did not take into account the output generated after the recycling process and the production of recyclates. This includes quantities for export, substance recovery and energy recovery as refuse-derived fuel (RDF). . Therefore, on the basis of EU Implementing Decision 2019/665, the calculation method was adapted that adds input (prepared secondary material) to the process stage of compounding or processing.

Production waste is more unmixed and uncontaminated than post-consumer waste. Therefore, a proportion of **74 percent** was sent for material recovery.

Post-consumer waste, by contrast, is characterised by packaging that has not been completely emptied, composite packaging, contaminated packaging and other wrongly disposed of items, with the result that only **around 45 percent** (input in first recycling plant) or, using the new EU Implementing Decision 2019/665, just under 33 percent (input in the process stage of compounding or processing), was recovered as substances (cf. Table 1).

The largest amount of 54 percent (or around 66 percent in line with the new calculation method of EU Implementing Decision 2019/665) is recovered as energy.[6]

Table 1: Volumes of Plastic Waste in Germany 2021[7]

	Total Plastic Waste		Post-Consumer Waste		Waste from Production and Processing	
	million tonnes	%	million tonnes	%	million tonnes	%
Substance recovery	2.64	46.6	2.47	45.4	0.17	73.9
of which raw materials recovery	0.03	0.5	0.03	0.6	0.00	0.00
of which materials recovery	2.61	46.0	2.44	44.8	0.17	73.9
Recovery as energy	2.99	52.7	2.94	54.0	0.05	21.8
Disposal/landfill	0.04	0.7	0.03	0.6	0.01	4.3
Total waste volume	**5.67**	**100**	**5.44**	**100**	**0.23**	**100**

If all losses and outputs used elsewhere are actually considered, which also arise behind the newly set calculation point of EU Implementation Decision 2019/665, the result is 1.46 million tonnes of plastic waste that were sent to material recovery in 2021 (cf. Figure 1). In terms of the quantity of post-consumer waste, this equals a **recycling rate of 26.8 percent.**[8] In 2017 and 2019 this rate was still 15.6 percent (810,000 tonnes) and 19.2 percent (1.03 million tonnes), respectively.[9, 10] Continuous growth of 7.6 percentage points since 2019 and 11.2 percentage points since 2017 has been seen.

6 Cf. Lindner, C. et al. (2022), p. 13.
7 Cf. Lindner, C. et al. (2022), pp. 18f.
8 Cf. Lindner, C. et al. (2022), p. 20.
9 Cf. Lindner, C.; Schmitt, J. und Hein, J. (2020), pp. 13ff.
10 Cf. Arkin, C. et al. (2021), pp. 36f.

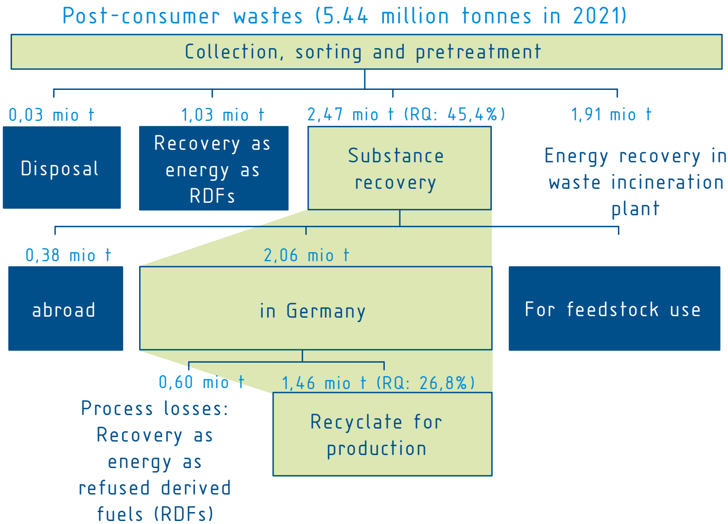


Figure 1: Plastic Substances Stream Germany 2021 (own figure)[11]

Exported Plastic Waste

The amount of **exported plastics** was approx. one million tonnes in 2020 and fell by eight percent in comparison to 2019.[12] This equals an export rate of approx. 17 percent relative to total plastic waste (6.28 million tonnes) in 2019. Plastic exports were reduced again in 2021, among other things due to import restrictions, which were imposed by China in 2018 and subsequently by other Asian states, and stricter regulations in the Basel Convention, implemented on 20 December 2020. For 2021, they were 766,000 tonnes, corresponding to an **export rate of 13.5 percent**.[13] In addition to the reasons cited, the fall is also due to the coronavirus crisis and the associated interruptions to supply chains, as well as to rising domestic demand for raw materials. Revenue from exports remained relatively constant at a total of approx. € 259 million, in spite of the drop in volumes.[14]

[11] Own figure based on Cf. Lindner, C. et al. (2022), p. 19.
[12] Cf. Statistisches Bundesamt (2021).
[13] Cf. Statistisches Bundesamt (2022a).
[14] Cf. Der Tagesspiegel (2022).

Use of Plastic Recyclates

In 2021, a total of 14.04 million tonnes of plastic was processed. Of these, 11.75 million tonnes were virgin grade. The **use of plastic recyclates** (1.65 million tonnes) including the reuse of by-products (0.64 million tonnes) amounted to approx. 2.29 million tonnes and therefore equals a share of 16.3 percent. In 2019, the share of plastic recyclates including by-products was still 1.95 million tonnes with a share of 13.7 percent.[15] That represents an increase of 340,000 tonnes. The use of plastic recyclates from post-consumer waste that this includes rose from 1.02 million tonnes in 2019 to 1.27 million tonnes in 2021 - this is an increase from 250,000 tonnes. Most plastic recyclates were processed in the construction industry (40 percent), in the packaging industry (29 percent) and agriculture (eleven percent).[16]

2.1.2 Statutory Challenges

The **regulatory objectives** for closing the plastic cycles in the European Union (EU) and in Germany are ambitious. The EU Action Plan for the Circular Economy of 2015 and the new EU Action Plan for the Circular Economy of 2020, which was announced in the European Green Deal of 2019, forced sustainable dealings with plastics with comprehensive packages of measures and directive specifications. The statutory requirements range from sustainable packaging design and a ban on single-use plastics to stipulating a binding recyclate proportion in certain plastic products. Alongside further packages of measures, the European Plastics Strategy laid down implementation of a single-use plastics directive, which was published in 2019 and was to be transposed into national law by 2021.

At **national level** the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) published the “5-Point Plan for Less Plastic and More Recycling”[17]. Just like the European regulations, this demands upscaling of recycling capacities, for example, and the increased use of recyclates in products. The European Union requirements were implemented in Germany by revision of the Circular

[15] Cf. Lindner, C.; Schmitt, J. und Hein, J. (2020), p. 13.
[16] Cf. Lindner, C. et al. (2022), p. 20.
[17] Cf. BMUV (2018).

Economy Act in 2020 and other, in some cases still ongoing, legislative pro-cesses (cf. Figure 2).

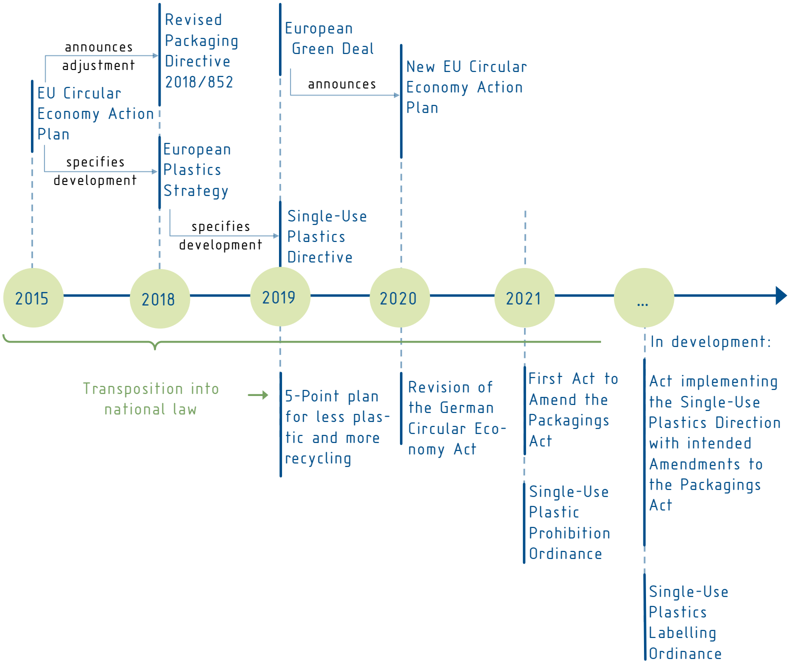


Figure 2: European and National Regulations on Handling Plastics (own figure)

The extract from the currently most important statutory regulations at European and national levels clearly shows the high standing attached to handling plastics. However, practical implementation of the statutory regulations is bureaucratically **demanding and complex**. Therefore, the European Union requirements are transferred to national legislation in different ways in the member states. For example, this includes different collection and recovery system, including those based on different targets for recovery rates or different deposit systems.[18, 19]

[18] Cf. Kunz Rechtsanwälte (2021). [19]
Cf. Schiller, C. et al. (2020), pp. 44ff.

Even at national level, the statutory requirements are extensive and can vary from one federal state to another. In addition to different requirements in the EU member states, in Germany, for example, there are inconsistent conditions nationally on the transport of pre-sorted plastic waste or with respect to the implementation and monitoring of the separate collection of plastic waste in line with the Commercial Waste Ordinance. For companies, often trading globally, the **fragmented legislation** represents a great deal of work, meaning that economic incentives, for example a lower licence fee for packaging designed to be easily recyclable, sometimes remain unused.[20]

2.1.3 Challenges in Practice

The players in the plastics value chain (cf. Figure 3) show promising potential with respect to establishing a circular economy, but have to face up to the challenges that need to be mastered.

A key aspect for establishing a functioning, circular plastics market is exchange among the players all along the value chain. Such an exchange fosters a comprehensive understanding of the processes of other stages of the value chain and helps to reveal relevant potential for improvement. This requires the identification of existing challenges that were named as follows on the basis of a **two-year dialogue process** among all of the players in the plastics value chain.[21]

[20] Cf. Schiller, C. et al. (2020), pp. 44ff.
[21] Cf. VDI e.V. (2022).

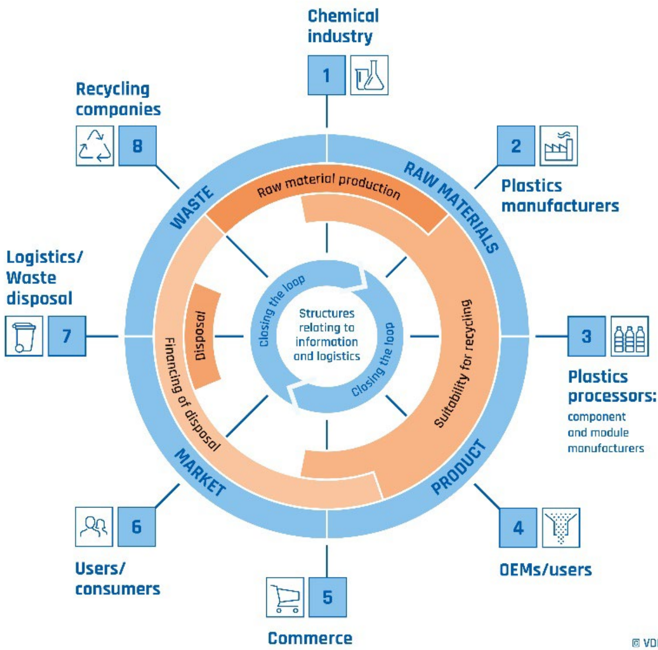


Figure 3: Players in the Plastics Value Chain © VDI e.V.[22]

(a) There are no comparable competitive conditions between recyclates and plastics from fossil raw materials[23]

Currently, there is no balanced competition between plastic recyclates and virgin ware (new plastics). For this reason, companies are demanding that products suitable for the circular economy, especially those containing recyclates, are placed in a better position by means of economic incentives in order to remove market distortions to the benefit of such products. For example, this concerns bonus and penalty systems for sustainable industrial and consumer packaging. The reduction of greenhouse gas emissions resulting from the use of recyclates should be pointed out and used for an improved positioning of circular products, including using tradable CO_2 certificates as part of the Emissions Trading System (ETS).

[22] © VDI e.V. (2022). Reproduced with the permission of Verein Deutscher Ingenieure e.V.

[23] Cf. VDI e.V. (2022), p. 3.

(b) There is an imbalance in supply and demand in the market for recyclates.[24]

The plastic recyclates market shows a discrepancy between strong demand for plastic recyclates from manufacturers and limited supply from the recycling industry, which in turn complains about small sales markets and competitive disadvantages. This is primarily a quality problem: the available plastic recyclates often do not satisfy the qualities demanded by industry. Sufficient quantities of recyclates of low quality are therefore available for simple products, such as park benches, paint pots or flowerpots, but are not bought by industry because it is more economical to use virgin ware because of the low oil price. Although manufacturers are demanding high-quality plastic recyclates - also due to rising pressure from customers -, sufficient and continuous amounts are not available.

Plastic Recyclates standardisation

In recent years, **certification systems** that evaluate plastic recyclates according to set criteria have been established. These include certificates such as EuCertPlast and flustix RECYCLED from DIN CERTCO. Among other things, these prove the origin of the recyclate, view the recycling process (including the entire supply chain) and evaluate the quality assurance process undergone as well as continuous availability.[25]

In addition, in December 2021, **DIN SPEC 91446** “Classification of Plastic Recyclates by Data Quality Level for Use and the (Internet-Based) Trade” was published. The standard distinguishes between and classifies plastic recyclates in three data quality levels. This makes the characterisation of plastic recyclates easier and supports communication for the players in the value chain.

Furthermore, DIN SPEC 91446 acts as a basis for a subsequent European standard and thus supports the den globally aligned plastics market.[26]

[24] Cf. VDI e.V. (2022), p. 4.
[25] Cf. Lange, U. (2021).
[26] Cf. DIN e. V. (2021).

(c) A fragmented value chain dominates in the plastics industry.[27]

The plastics industry is made up of various players of different sizes with diverse product and material requirements. A few large plastics producers and many small and medium-sized processors, waste disposers and recyclers form a fragmented wealth creation structure. The joint transformation process towards a resource-efficient circular plastics economy therefore faces many different challenges and needs intensive cooperation and coordination along the entire wealth creation process.[28]

(d) There are technological limits and conflicting objectives.[29]

Due to their properties (lightweight, food-safe, printable, flexible, etc.), plastics are suitable for many different uses. For example, in the food sector it is possible to extend the shelf life of packaged products. Often, such packaging, etc. is made from composite materials or material mixes that cannot be recycled using standard mechanical methods (cf. Chapter 2.2). Although there are other collection and recycling solutions offering recovery, they sometimes need increased use of energy and raw materials. An evaluation of intended solutions therefore presupposes a consideration of the entire life cycle. The possible expenses should not exceed those for the manufacture of products from primary raw materials so that an actual saving of greenhouse gas emissions is achieved.

Example of Good Practice: Recyclate Initiatives

Recycling initiatives are alliances of players from research, industry and politics who study and develop circular economy structures and identify challenges as to how an ecologically and economically sustainable circular economy can be implemented in practice - especially with respect to the use of secondary raw materials. Thus, the **Recyclates Forum** to promote the circular economy was founded in 2018. Its more than 60 members mainly come from commerce, manufacture, disposal and packaging manufacture and are divided into the four divisions “Master Data

[27] Cf. VDI e.V. (2022), p. 4.
[28] Cf. VDI e.V. (2022), p. 4.
[29] Cf. VDI e.V. (2022), p. 4.

Management", "Technology and Recyclability", "End Consumer Communication" and "Packaging Reduction", for which the members develop strategies and measures.

For example, in the Master Data Management" division, the depiction of recycling shares in packaging materials was implemented in the Global Data Synchronisation Network (GDSN). This enables transparent transfer of information in the supply network and smooth retrieval of data from the value creation stages.

This step, in turn, smooths the way to the establishment of product passports, which can foster the realisation of a resource-efficient circular economy even more.[30]

(e) Political regulation to date has been aimed at waste.[31]

In 2012, the former German Closed Substance Cycle and Waste Management Act was replaced by the currently applicable German Circular Economy Act. Nevertheless, the statutory regulations are strongly geared towards the end of life phase. This focus changed only recently. The shape of the statutory regulations is focusing increasingly on the entire value chain and making demands of every player. For example, this includes the EU's **Green Deal** for example, the Plastic Strategy or the Circular Economy Action Plan) and the **Ecodesign Directive**.

[30] Cf. Forum Rezyklat (2022).
[31] Cf. VDI e.V. (2022), p. 5.

Current Developments in Chemical Recycling

Currently, the focus of specialist discussions has returned to the importance of chemical recycling. With the help of chemical recycling or what is known as raw materials recovery, plastics are broken down into their chemical components and returned to the value chain in the form of alternative raw materials. Since chemical recycling is characterised by energy-intensive processes, the technologies were unable to establish themselves in past decades for reasons of life cycle assessments and for economic reasons. Technical solutions have therefore been working only as pilot or demonstration systems to date.

However, current developments and innovations show that chemical recycling has developed further technically and ecologically. In particular, chemical recycling offers an alternative for material compounds that cannot be recovered using mechanical recycling.

As a supplement to mechanical recycling it is thus possible to develop further substance flows for returns to the economic cycle (cf. Chapter 2.3.2) and successively replace primary raw materials.

(f) The pressure on the plastics industry from public communications to act is high.[32]

In particular, the public focus has been drawn to plastic waste due to reports about the growing quantities of plastics in the oceans. Social pressure on the plastics industry to offer sustainable solutions is therefore increasing continuously. It should pursue a systematic approach in order to guarantee a comprehensive transformation of the value chain and create a uniform basis for communication.

[32] Cf. VDI e.V. (2022), p. 5.

Development of a Recycling Label

In the Coalition Agreement of 2021, the Federal Government decided to introduce a recycling label.[33] Budget funds of € 600,000 were made available for this. This budget was to be used for the "creation of a concept for the content and organisational and procedural design of a recycling label as well as technical support for the introductory phase of the recycling label"[34].

The aim is to provide consumers with reliable and transparent information on the proportions of recyclates or secondary raw materials in products. In this way, a decision to purchase more environmentally friendly products will be successively facilitated and supported.

The listed challenges will be countered by various developments in the plastics industry. Both in practice in companies and in research, efforts are being made to improve and stabilise the cycle for plastics (cf. Chapter 2.3).

2.2 State of the Art

The **collection and sorting** of plastic waste (lightweight packaging and other recyclables from the recycling bin, post-consumer waste and commercial waste similar to household waste) is done according to the state of the art in various procedure stages that – depending on the system concerned – are arranged in different ways. In this way, more than ten different sorting fractions can be sorted and sent for further treatment (cf. Figure 4).[35]

[33] Cf. Bundesregierung der Bundesrepublik Deutschland (2021).
[34] Cf. Thews, M. (2022).
[35] Cf. Knappe, F. et al. (2021), p. 49f.

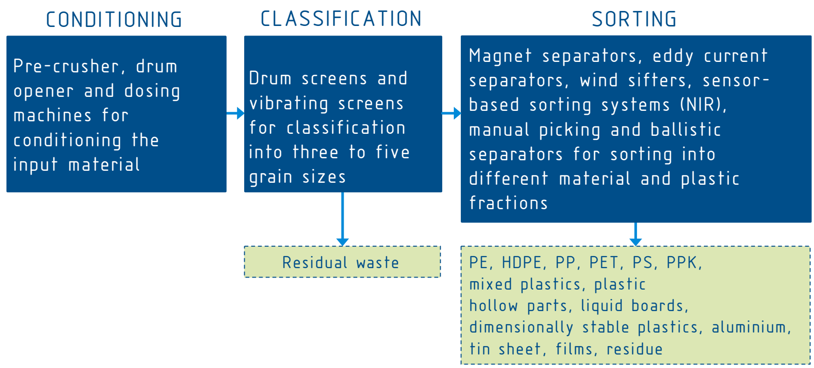


Figure 4: Collecting and Sorting Waste (own figure)[36]

According to Table 1, only 45.4 percent of the total input of post-consumer waste is sent to material recovery after collection and sorting. This situation is shown in the yield of product fractions with respect to the polymer content of the input (cf. Table 2).

Table 2: Yield from Sorting per Substance Fraction[37]

Substance Fraction	Yield relative to Input per Substance Fraction
PE	52% by mass
PP	49% by mass
PS	48% by mass
PET	95% by mass
Film fraction (> DIN A4)	32% by mass

The remaining volume flow cannot be screened out due to contamination, items being disposed of incorrectly, etc. and ends up in recovery as energy. However, there are now sorting systems that achieve higher sorting rates. A Good Practice plant for the sorting of post-consumer waste and commercial

[36] Own figure based on Knappe, F. et al. (2021), p. 49.
[37] Knappe, F. et al. (2021), p. 53.

waste similar to household waste installed in 2018 is already capable of generating an output of around 53 percent (in terms of the total input) which can be sent for material recovery.[38] The PET material flow, which can be screened almost completely or collected separately, is an exception here.

After sorting, the sorted or separately collected fractions go to **material recovery**. A combination of different dry and wet mechanical methods for separating impurities and to create plastic products with defined properties has been established for the manufacture of regrind, agglomerate or regranulates cf. Figure 5).

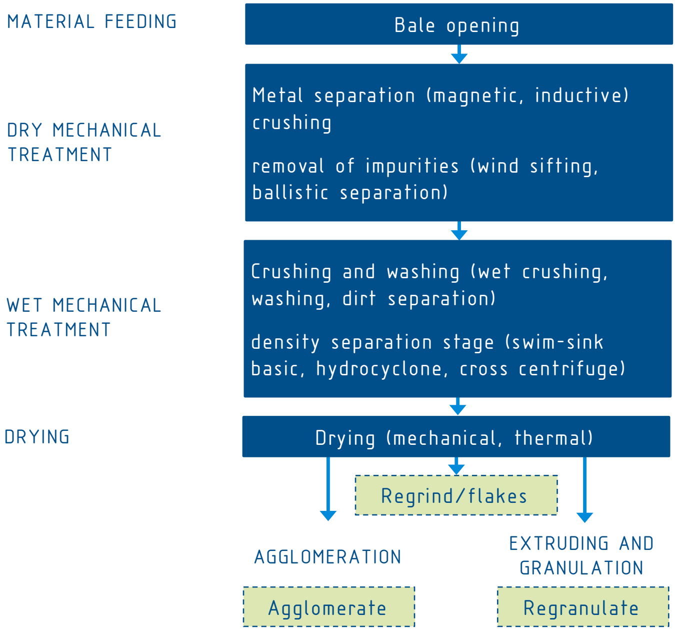


Figure 5: Material Recovery (own figure)[39]

Examples from practice show that plants installed according to the state of the art are already capably of generating good quality recyclates. With special methods of pre-sorting and cleaning, even scent clingage can be removed

[38] Cf. MEILO Gesellschaft zur Rückgewinnung sortierter Werkstoffe mbH & Co. KG (2022).
[39] Own figure based on Knappe, F. et al. (2021), p. 73.

from cosmetics and toiletries packaging in one case and pots, trays or bottles can be recycled into new products of the same kind.[40] This form of material treatment enables plastic recyclates to be used again for their original purpose. In particular, cooperation across value chain stages enable a more efficient design of substance flows. In this way, in another example, PP and HDPE packaging material could be manufactured with the help of recyclates from the recycling bin and the cycle was thus closed directly.[41]

2.3 Innovative Recycling Technologies

In addition to tried and tested recycling technologies, there are various other developments for sorting plastics that will be explained in more detail below. At this point, it must be pointed out that the development of recycling methods must always be followed **against the background of digitisation**. For example, products such as “AIOptiPack – Holistic AI-based Optimisation of Plastic Packagings containing Recyclates” and “A3I-Cycling – AI-based Optimisation of the Closed-Loop Circulation of Plastic Packagings” deal with the digital networking of all value chain stages on the use of artificial intelligence to close the plastics cycle for packaging.[42]

2.3.1 Sorting Plastic Materials

Detection of Black Plastics

The sorting of plastic waste is subject to the fundamental problem that **black plastics** in particular cannot be removed from the flow of recyclables. In the sorting process, near infrared (NIR) scanners light up the passing plastics. The reflected near infrared spectrum is measured and analysed. Every type of plastic has a typical spectrum and is screened out by downstream compressed air jets. Soot is used to colour the plastics black, which absorbs the majority of the radiation in the visible and the infrared wavelength range. The detectable spectrum has too low an intensity to be recognised by the NIR scanners. This usually makes sorting according to plastic type impossible.

[40] Cf. Ministerium für Klimaschutz, Umwelt, Energie und Mobilität des Landes Rheinland-Pfalz (2022).

[41] Cf. VDI Zentrum Ressourceneffizienz GmbH (2018).

[42] Cf. Fraunhofer-Institut für Verfahrenstechnik und Verpackung IVV (2023).

There are already sorting technologies on the market that are able to screen out black-coloured plastics. A **sorting system has been developed** for this that can be connected downstream of a lightweight packaging system for the accumulation of dark items. With the use of Hyper Spectral Imaging (HSI) technology in the mean infrared range, even soot-coloured items sized between 10 and 40 millimetres can be detected and positively screened out.[43] These plants can be integrated in existing sorting plants, but need sufficient space and high levels of investments.[44]

Detectable Black

Product development has already reacted to the challenges of the sortability of black plastics. One company has developed a black pigment with high coverage and satisfies requirements for sensitive applications, such as food packaging. The pigment can be recognised by NIR scanners and screened out accordingly. According to the manufacturer, it has a high degree of processing stability – even across several processing stages – and can therefore be considered for closed recycling cycles. However, its use in closed recycling cycles presupposes that there is no mixing with other black plastics.[45]

Separation by Means of Electrostatic Charging

The use of **electrostatic separators** is an established, but alternative, way of separating plastics without using optical systems. Here, the plastic types are charged according to their properties in a charging unit. For example, in an ABS-PS mix, the polystyrene takes on a negative charge while the acrylonitrile butadiene styrene takes on a positive charge. In a subsequent electrode systems, plastics can be separated from each other with high degrees of purity. The technology requires that plastics to be separated are dry, open and free of dust and, ideally, are a two-substance mix. The method has already established itself for the separation of rubber from PVC from window

43 Cf. Knappe et al. (2021), p. 51f.
44 Cf. Knappe et al. (2021), p. 111.
45 Cf. packaging journal (2020).

profiles, for beverage bottles and the separation of PS and ABS from electrical and electronic waste.[46, 47]

Use of Markers

What is known as **markers** are another way of separating plastics. As part of cooperation between three companies, a marker has been developed that is printed on products. For this, **UV screen printing inks** are used with a defined spectrum. With the help of an update, this information is integrated in the analysis tool of the NIR scanner so that, for example, food packaging are separated from non-food packaging or unrecyclable products can be screened out of the material flow. This procedure increases the purity and therefore the quality of the plastic flow sent for material recovery.[48]

Another example uses **fluorescence-based markers** to enable sorting.[49] This marker is applied either in the product or on the label and has a specific spectrum that can be picked out using fluorescence spectroscopy. What is known as **Tracer-Based-Sorting (TBS)** allows plastic packaging to be separated irrespective of shape, colour and contamination and to be recovered specifically for the original purpose. Old food packaging, for example, can be processed into food packaging again.[50] Moreover, it is possible to identify more plastic types and various kinds of a plastic type. Studies have shown that recognition of almost 100 percent can be achieved using this technology.[51] In cooperation with a company in the optical industry, a sorting technology – building on fluorescence markers – has been developed that combines several **detection technologies**. These include Tracer Detection, NIR (near infrared) measurement, colour measurement and image detection (AI – Artificial Intelligence) as well as, where applicable, detection of a watermark. The system is available in Freiburg as a pilot system for experimental procedures for interested players from the circular economy.[52] Pilot tests are relevant because Tracer-Based Sorting is a **complex innovation**. A

---

[46] Cf. Köhnlechner, R.; Jung, H. und Geisler, W. (2012).
[47] Cf. hamos GmbH (2023).
[48] Cf. Brunn, M. (2021).
[49] Cf. Polysecure GmbH (2022).
[50] Cf. Ecologic Institut gemeinnützige GmbH (2022).
[51] Cf. Ecologic Institut gemeinnützige GmbH (2022).
[52] Cf. EU-Recycling Magazin (2022b).

broad implementation of the technology in practice has impacts on the entire value chain and needs adaptation of the sorting technologies currently used. In addition, there are further challenges related to the marking location. Placing the marker on the label enables sorting of entire products. However, subsequent flake sorting of the crushed products is no longer possible using markers. If the marker is integrated in the product, this requires closed cycles. The product must be used for its original purpose because otherwise there are carryovers or commingling of the markets in substance recovery, which hamper further sorting.[53]

Another sorting technology based on markers that have been placed is the **digital watermark**. The HolyGrail 1.0 project ran from 2016 to 2019 and, with project members from the whole plastics value chain, examined the potential of digital watermarks as a sorting technology. With this technology, the label or the surface of packaging was repeatedly printed or embossed with an imperceptible optical code at least one square centimetre in size. Colour cameras recognise or scan the code and, due to the stored properties, can undertake a more specific sorting in comparison to classic separation. The digital marking can be printed repeatedly over the whole surface of the packaging. This means that position is irrelevant and there is a certain tolerance to dirt and damage. The digital watermark is erased by crushing of the packaging and is no longer usable for subsequent sorting of the flakes, which are mostly smaller than one square centimetre.[54] At the end of the project, a proof-of-concept was presented and the method demonstrated using a test sorting plant. The **HolyGrail 2.0** planned project takes up the findings of the preceding project and aims to upscale the technology to industry level. Studies are currently running on a pilot plant. A developed detector unit for sorting packaging material from plastics and fibre composites achieved an average detection rate of 99 percent, a screening rate of 96 percent and a purity degree of the sorted fractions of 93 percent (cf. Table 3).[55]

---

[53] Cf. Krüger, F. (2020), p. 19.
[54] Cf. Krüger, F. (2020), p. 21.
[55] Cf. Digital Watermarks (2022).

Table 3: Sorting Results of the Use of the Digital Watermark[56]

Fraction	Detection Degree	Sorting Degree	Purity Degree
PP	99.6%	99.6% by weight	94.2% by weight
PET	99.1%	95.7% by weight	92.6% by weight
Fibre composites	98.9%	97.0% by weight	93.1% by weight
PE Films	97.6%	92.0% by weight	90.8% by weight

As a result of the successful conclusion of the studies, the technical readiness level has been brought to TRL 6 (prototype in operational environment). The aim of the project is to achieve technology readiness level TRL 9 (qualified system with proof of successful deployment) after the end of all the studies.[57]

Use of Product Passwords

The advantage of the markers described is the additional storage of attributes. Thus, for example, information on the manufacturing company, the stock keeping unit (SKU), type of plastic used and composition, food safety, amount of recyclates, etc. can be stored.[58] In this way, the technology is also **relevant to product passports**, which will possibly enable the passing on of information across the value chain.

A cross-sector consortium was formed for this, which is working on an **open traceability standard that can be used worldwide** (digital product passport). The aim is to trace recyclable packaging along the value chain and enable continuous documentation. The information can be read out via a marking on the packaging – for example a QR code or a digital watermark – , is based on the GS1 standards[59] and stored on a common data platform.[60] Within the consortium, various pilot projects have been launched by members that test the feasibility of the digital product passport in the form of markings in practice. One of the pilot projects developed a data recording system as an interface between an extrusion blow-moulding plant and the platform that transfers the manufacturing data in real time. At the end of the life cycle, it should be possible for waste sorting systems to read out the data

[56] Digital Watermarks (2022).
[57] Cf. AIM - European Brands Association (2021).
[58] Cf. AIM - European Brands Association (2021).
[59] Cf. GS1 Germany GmbH (2022).
[60] Cf. R-Cycle (2022a).

with standard detection technologies and then for the waste to be sorted correctly.[61]

In particular, the transparent transfer of product information along the whole value chain is a hot topic. A **recyclate initiative** with more than 60 members is currently developing and studying strategies and measures, among other things on master data management. The aim is to create a uniform and digitally processable data base that can be used nationally and internationally. With the cooperation with GS1 Germany it will be possible, among other things, to depict the recyclate content of packaging materials in the Global Data Synchronisation Network (GDSN) – the worldwide alliance of certified master data pools. In this way, relevant product data can be communicated transparently along the supply and value chains.[62]

The K3I-Cycling project launched in September 2022 also aims to develop **a lightweight packaging product passport** with the help of an Artificial Neural Twin. In this case, too, the aim is to transfer relevant information along the plastics packaging value chain in order to contribute to optimising the entire system.[63]

All of the measures and projects presented with the aim of providing information along the value chain enable better traceability of materials and goods. Assessments from practice suggest that although these technologies are successively tapping into new markets, they are not yet capable of replacing the current technology. Instead, they are a **supplement and optimisation**. The following advantages are highlighted:[64]

- Separation of food and non-food packaging
- Targeted rejection of quality-reducing content
- Colour sorting

[61] Cf. R-Cycle (2022b).
[62] Cf. Forum Rezyklat (2022).
[63] Cf. Fraunhofer-Institut für Verfahrenstechnik und Verpackung IVV (2023).
[64] Cf. DGAW – Deutsche Gesellschaft für Abfallwirtschaft e.V. (2021).

- Quality transparency

Moreover, the waste disposal sector is demanding more points for the future that foster more efficient plastic recycling. These include packaging that is (even) more suitable for recycling, more intensive cooperations between all involved in the value chain and an increase in demand for recyclates.[65]

2.3.2 Recovery into Plastic Recyclates

After sorting, the plastic fractions are mainly recovered as materials (cf. Chapter 2.2). In addition to tried and tested **mechanical recycling technologies,** new methods have been developed, especially in raw material or **chemical recycling**. Here, it must be pointed out that chemical recycling should be viewed as a **supplement to the standard** mechanical recycling technology. This is especially the case for plastic waste flows, such as mixed plastics, that can only be recovered inadequately by means of mechanical recycling. New requirements for the product design of plastic packaging (such as the use of monoplastics) should result in increasing unmixed sorting fraction. In this way, further quantities of plastic recyclates can be tapped into via mechanical recycling as a standard technology. As an alternative technology, chemical recycling is capable of increasing further secondary raw material potentials for the sorted fraction of mixed plastics as well as for other specific plastic waste flows.

Chemical Recycling of Mixed Plastics

In this regard, Rittec Umwelttechnik GmbH has developed a new technology that breaks mixed plastics containing PET into their monomers. The PET monomers can be reused for the manufacture of items with the quality of virgin ware. This technology came about in close cooperation with the Institut für Chemische und Thermische Verfahrenstechnik at Braunschweig University. In the research and development phase, it was proved that more than 45 percent of CO_2 emissions were saved with this method in comparison to production with new PET from crude oil. The patented **revolPET®** technology is characterised by the continuous depolymerisation of the polyester pol-

[65] **Cf. DGAW – Deutsche Gesellschaft für Abfallwirtschaft e.V. (2021).**

ymer into the basic building blocks of terephthalic acid (TA) and monoethylene glycol (MEG). This process is carried out on the basis of a solid-solid reaction in a standard extruder, in which the reaction energy released is used directly to accelerate the subsequent reactions. Process times of less than one minute were achieved, within which 95 percent of the PET polymers were broken down. During this process, the remaining residual materials do not react and can be sent for further recovery after the PET has been dissolved out.[66] The method can already be used economically for medium-sized capacities and can thus be linked to decentrally available secondary raw material flows.[67]

The **Newcycling®** method from APK AG, another patented recovery method, recovers mixed plastics and multilayer packaging to manufacture unmixed granulates of LDPE and with similar properties to primary plastics. For this, the bales delivered from household and commercial collections are opened and crushed, the plastic flakes washed and separated from each other by gravity. The plastics are then selectively dissolved in a solvent bath. A multistage process follows in which first of all the liquid components are separated from the solid components, the polymer cleaned and the solvent removed. The solvent is then retreated and can thus be returned to the Newcycling® process again. The company's aim is to extend the product range of the LDPE and PA regranulates currently produced with further target polymers – such as PP and PVC.[68]

The large number of new, sometimes recyclate-specific projects and technological developments reflects the relevance of plastic recycling today. A selection is shown in the table below (cf. Table 4).

[66] Cf. RITTEC Umwelttechnik GmbH (2022).
[67] Cf. Paschetag, M.; Scholl, S. und Eichert, C. (2022).
[68] Cf. APK AG (2022).

Table 4: Selection of Projects on Innovative Recycling Technologies for Plastics

Recycling Method	Resultant Recyclate	Brief Explanation of the Technology	Source
Upcycling of PET, material development from used PET	New material based on PET	A new material has been manufactured on the basis of used PET bottles that has similar mechanical properties to short glass fibre-reinforced polyesters or polyamides, A demonstrator component made from it had low shrinkage, high dimensional stability and a much improved CO_2 footprint. A follow-on project is studying the development of components from PET packaging waste that cannot be sent for material recovery. [69]	Fraunhofer LBF (2021), Press Release
Modern pilot system for the manufacture of marketable polymer materials	Films and solid plastic household waste	In Lahnstein, two companies, Borealis and TOMRA, operate a mechanical recycling system on a pilot scale, by means of which the polyolefines generated have a high degree of purity, low odour, high product consistency and only minor colour deviations and can therefore be used for high-quality plastic applications.[70]	Borealis Group (2021), Press Release
Mechanical Recycling of PE/PA Compounds	PE/PA	A study that has been commissioned proves that the mechanical recycling of PE/PA compounds is not only technically possible, but that the properties of the PE recyclate thus produced is actually positively influenced by the compound. A trial with other compounds has been started. As a next step, recycling implementation on an industrial scale is planned.[71]	BASF (2021), Mechanical Recycling
Chemical Recycling using the CreaSolv® Method	PVC	In a research project, the CreaSolv® method is used to separate additives such as phthalates from old PVC floor coverings. They are hydrogenated and therefore achieve REACH conformity. The PVC from the CreaSolv® process can be manufactured into new PVC for the production of floor coverings by adding either new stabilisers or recycled plasticisers.[72]	Fraunhofer IVV (2022), Circular Flooring Research Project
Chemical Recycling using the iCycle® method (Pyrolysis)	Miscellaneous	New types of patented heat exchanger technologies ensure a particularly energy-efficient pyrolysis process and better heat transfer to the material to be recycled. The process is especially suitable for shredder residues, among other things, and can screen out or eliminate harmful substances, such as halogens.[73]	Fraunhofer Umsicht (2022), iCycle® Method

[69] Cf. Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit LBF (2021).
[70] Cf. Borealisgroup (2023).
[71] Cf. Newsroom Kunststoffverpackungen (2021).
[72] Cf. Fraunhofer-Institut für Verfahrenstechnik und Verpackung IVV (2022).
[73] Cf. Fraunhofer UMSICHT (2022).

2.3.3 Recovery Technologies with a Biological Basis

Some enzymes have the ability to break down plastics. In 2012, for example, the **enzyme LCC** (Leaf-Branch Compost Cutinase) was discovered on a compost heap in Japan. It is a polyester-splitting hydrolase and can break PET down into its components terephthalic acid (TA) and monoethylene glycol (MEG). Research and development picked up these research results and looked for and examined other polyester-splitting hydrolases. For example, researchers from the Institute for Analytical Chemistry at Leipzig University identified seven other enzymes that are capable of breaking down amorphous PET. One of these biocatalysts, **the enzyme PHL7**, broke down 90 percent of a specified quantity of PET within 16 hours. By way of comparison, under the same conditions, the enzyme LCC broke down only 45 percent of the PET. The reason for this lies in a component difference between the two enzymes. Whereas in the enzyme LCC one place is occupied by the amino acid phenylalanine, this place is filled with the amino acid leucine in the enzyme PHL7.

One advantage of enzymatic recycling lies in the low-energy recovery conditions, which only require an aqueous solution and temperatures between 65 and 70 °C. Other research work is looking at the transferability of the biodegradability of amorphous PET (for example, packaging trays for fruit and vegetables) to stretched PET (for example, beverage bottles).[74] Currently, a co-operation between two companies is planning to build a production plant for the biological recycling of PET in France. The plant is set to start operations in 2025.[75] The technology behind this is in particular characterised by the fact that all types of PET can be broken down by enzymes. The enzyme used for this has been adapted and optimised for this purpose. Food-safe sample bottles have already been manufactured with enzymatically recycles PET in a demonstration system that has already been successfully implemented.[76]

However, here it must be pointed out that the cycle for PET is already largely closed with standard recycling technologies (cf. Table 2). An alternative tech-

[74] Cf. Schick, B. (2022).
[75] Cf. Bechlarz, D. (2022).
[76] Cf. Plastverarbeiter (2021).

nology for PET recycling is therefore a supplement. With a view to the continuous availability of quantities and associated efficiency, it therefore remains to be seen whether the method will be able to hold its own against established PET recycling methods.

3 BATTERIES AND RECHARGEABLE BATTERIES

3.1 Challenges in Battery Recycling

The market for the manufacture and recycling of batteries and rechargeable batteries is subject to dynamic growth. In particular, the demand for and manufacture of lithium-ion batteries are currently growing rapidly. Therefore, recycling capacities that are not currently available will be built up successively in order to adequately recycle the increasing quantities of lithium-ion batteries. The question as to upscaling recycling capacities for industrial batteries, especially lithium-ion batteries in Germany, has been discussed in a technical discussion with experts from the battery market. The results can be found in the second part of this brief analysis "Results of the Technical Discussion".

3.1.1 Current Recycling Situation

Whereas lead-acid batteries in particular are currently collected and recovered, in future an **enormous rise (in demand) for lithium-ion batteries** is expected, which ultimately will also have to be sent for adequate recycling. Currently, lithium-ion batteries are (still) assigned to the category 'Other Batteries' in the collection statistics (cf. Table 5). These include, among others, lithium-iron-phosphate (LFP), alkaline manganese (AlMn) and zinc-carbon (ZnC) waste batteries. The rise in reported quantities of this category noted since 2018, is mainly due to lithium-ion batteries, but also lithium-iron-phosphate batteries.

Meanwhile, recycling efficiencies of up to more than 80 percent can be achieved for all waste battery categories. According to Recycling Efficiency Regulation (EU) 493/2012, 'recycling efficiencies' refers to the ratio of input (mass of waste batteries sent to a recycling method) to the output (mass of the recovered secondary raw materials). This equals a mass of approx. 146,500 tonnes that were recovered as secondary raw materials in 2020, including for the manufacture of new batteries. The statutory minimum recycling efficiencies of 65 percent for lead-acid batteries, 50 percent for other batteries and 75 percent for nickel-cadmium batteries have thus been met (cf. Table 5).[77]

Table 5: Quantity of waste batteries sent for recovery (all battery types, including device, vehicle and industrial batteries)[78, 79]

	Collected quan-tity*	Recycling efficiency	Collected quantity*	Recycling efficiency	Collected quantity*	Recycling efficiency
	2020		2019		2018	
Lead-acid batteries	150,943 t[80]	81.6% (65%)**	205,254 t	81.9% (65%)	200,410 t	80.6% (65%)
Nickel Cadmium Batteries	1,048 t	79.5% (75%)	1,353 t	77.6% (75%)	1,221 t	79.1% (75%)
Other Batteries	29,620 t	76.2% (50%)	22,315 t	75.5% (50%)	17,424 t	83.8% (50%)
Total	181,611 t		228,922 t		219,055 t	

*Quantity collected sent for recycling, ** In brackets: regulatory required minimum recycling efficiency

However, **new recycling capacities** need to be created for lithium-ion batteries in particular. In forecasts, it is assumed that the market volume of lithium-ion batteries in Europe will increase by an order of magnitude of ten by 2030 (cf. Figure 6).[81]

In this connection, the key driver is the growing popularity of electric mobility (electric vehicles, e-bikes, etc.), for which double-digit growth rates are predicted. However, device batteries (3C) and lithium-ion batteries for commercial vehicles and energy storage systems are also contributing to the market growth. Currently, it is estimated that around 70 kilotonnes of recycling capacity are available in Europe (cf. Results of the technical discussion, p. 113). This figure is highly volatile because the recycling market for lithium-ion batteries is growing strongly and the newly formed recycling structures still have to stabilise. This is countered by predicted quantities of lithium-ion batteries of around 100 kilotonnes in 2025 and 250 kilotonnes in

[77] Cf. Umweltbundesamt (2021).

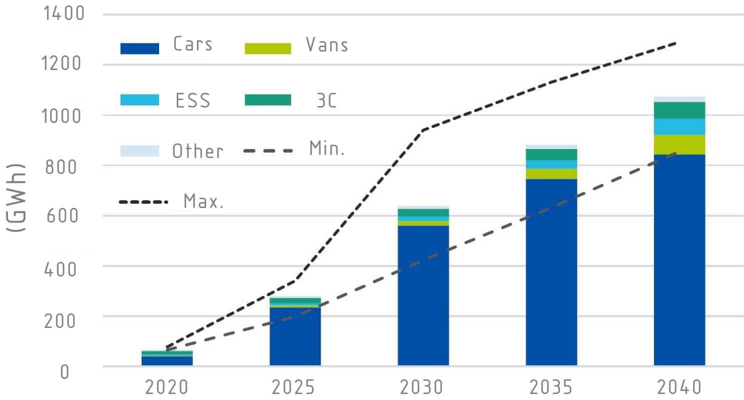
[78] Cf. ZVEI - Zentralverband Elektrotechnik- und Elektronikindustrie e. V. (2021).

[79] Cf. Umweltbundesamt (2021).

[80] The fall by approx. 50,000 tonnes of lead-acid batteries from 2019 to 2020 is due to the insolvency of a market participant who reported quantities of this order of magnitude in previous years (Interview Federal Environment Agency, 06.05.2022).

[81] Cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), p. 21.

2030, which will have to be sent for recycling.[82] For Germany, it is estimated that in 2030 the quantity of returned lithium-ion batteries will be approx. 50 kilotonnes (range from minimum 21 kilotonnes to maximum 78 kilotonnes). However, since the market for used vehicles in particular is strongly interconnected within Europe and scrap is exported and imported on a large scale, this prediction is a rough estimate.[83]



Car: Personal vehicle; Van: Commercial vehicle; ESS Energy storage system; 3C: Computing, consumer, communication; Other: e-bikes, scooters and other applications

Figure 6: Development of Demand for Lithium-Ion Batteries in Europe © Fraunhofer ISI [84]

3.1.2 Statutory Challenges

At European and national level, **a need for action was identified at an early stage** in order to react adequately to the dynamic market growth, especially of lithium-ion batteries.[85] In October 2017, the European Battery Alliance was set up to establish a “complete, internationally competitive and sustainable battery value chain in the EU”[86]. In addition, in May 2018, a dedicated strategic action plan for batteries was published within the context of the

[82] Cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), p. 22.
[83] Cf. Bittner, A. et al. (2021), p. 30.
[84] © Fraunhofer ISI; cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), p. 21.
[85] Cf. Halleux, V. (2022), p. 1.
[86] Europäische Kommission (2022).

third mobility package “Europe on the Move”. Key measures along the entire value chain of the ecosystem for batteries were listed in it.

Building on the Battery Alliance and the Action Plan, in December 2020 a proposal for **revision of the current Battery Directive** 2006/66/EC was also accepted by the European Commission. On 9 December 2022, the EU Parliament and the European Council agreed on a specific regulation for the new Battery Directive. The new directive is expected to become effective in 2023.

The revision is part of the European Green Deal and associated initiatives, such as the new plan of action for the circular economy and the new industrial strategy.[87] In particular, the plan of action for the circular economy prioritises dealings with the resource-intensive ‘Battery’ value chain.

The proposal considers the entire ‘Battery’ value chain and specifies the following **requirements,** among others[88]:

- The following applies to rechargeable industrial batteries and batteries for electric vehicles with internal storage and a capacity of > 2 kWh:
  - Battery manufacturers must adhere to requirements for the use of **responsibly sourced raw materials**.
  - Battery manufacturers must **submit** a declaration on their **CO_2 footprint** (from January 2026 this must be labelled on the battery and from July 2027 maximum values for the CO_2 footprint must be observed).
  - From 2030, a **minimum content of recycled cobalt, lead, lithium and nickel** must be used in the manufacture of these batteries. This minimum content will be increased in 2035. The recycled raw materials content must be stated from as early as 2027.
- Products must be designed by the manufacturing companies in such a way that the **batteries are easily removable**. The ability of the devices to function must not be impaired.

[87] Cf. Halleux, V. (2022), p. 2.
[88] Cf. Europäische Kommission (2020).

- The **collection rate** for device batteries should be **increased** – to 63 percent in 2027 and 73 percent in 2030.

The proposal contains further major changes and is classed as a **novelty** with respect to the **demands made of the entire** 'Battery' value chain.

However, the proposed changes result in further questions and challenges for the platers. In particular, there are uncertainties with respect to the rate of minimum content of recycled raw materials to be achieved from 2030. Among other things, the rate depends on factors such as the availability of end-of-life batteries, the technical limitations of recycling processes or any illegal shipments, especially of electric vehicles. However, any conflicts that arise are to be dealt with in a revision process planned in 2027 (cf. Results of the Technical Discussion, p. 91).

3.1.3 Challenges in Practice

The market for battery recycling is currently developing rapidly. This results in market economy challenges for players - from procurement and transport right up to disposal.

(a) Critical raw materials in lithium-ion batteries

The European Commission stipulated a classification of critical raw materials. This comprises raw materials that cannot be permanently and safely mined in Europe, therefore have to be imported and play a major role in the European economy. In total, 30 raw materials were classed as critical, including **lithium and cobalt**, for which supply security is not guaranteed for the European area.[89]

In addition, it has been estimated that the global cumulative demand for cobalt and lithium by 2050 will be less than the terrestrial reserves and resources (cf. Table 6).

[89] Cf. Strutzberg, L.; Lange, U. und Frerichs, T. (2022).

Table 6: Demand, Reserves and Resources of Lithium and Cobalt[90, 91]

	Lithium	Cobalt
Global cumulative demand by 2050	14 – 20 million t	6 – 9 million t
Globally available reserves (which can be mined economically according to the state of the art)	17 million t.	7 million t.
Globally available reserves (which cannot yet be mined economically according to the state of the art)	80 million t.	25 million t.

According to this, although there is a supply of raw materials per se, European or German markets depend heavily on countries in which the deposits are located geographically. Lithium is mainly found in Chile, Australia, Argentina and China, whereas half of the worldwide reserves of cobalt come from the Democratic Republic of Congo. The social conditions in which the mining takes place are heavily criticised here.[92]

An **evaluation of the raw material criticality** according to VDI Guideline 4800, sheet 2 once again illustrates this situation in detail. Thirteen different indicators measure the criticality of lithium and cobalt from low (0) to high (1). In addition, nickel was included as a raw material that was also relevant for battery production (cf. Table 7).

The criticality evaluation confirms the high-risk supply of raw materials markets in Europe and Germany from deposits centred in countries such as Congo, Chile and Argentina.

90 Cf. Fluchs, S. (2021), p. 1.

91 Cf. U.S. Geological Survey (2020), p. 51 u. p. 99.

92 Cf. Bundesanstalt für Geowissenschaften und Rohstoffe (2021), p. III.

Table 7: Raw Material Criticality of Lithium, Nickel and Cobalt according to VDI 4800, Sheet 2[93]

Category	Indicator	Lithium	Nickel	Cobalt
Geological, technical and structural indicators	Ratio of reserves to global annual production	0	0.7	0.3
	Degree of joint/ auxiliary production	0	0.3	0.7
	Distribution of functional end-of-life technologies	1	0.3	0.7
	Efficiency of storage and transport	0	0	0
	Distribution of natural deposits/cultivation areas	0	0	0
Geopolitical and regulatory criteria	Herfindahl Hirschman Index Country concentration of the reserves	1	0.7	0.7
	Herfindahl Hirschman Index Country concentration of production	1	0.3	1
	Political country risk	0.3	0.3	0.7
	Regulatory country risk	0.3	0.3	0.7
Economic criteria	Herfindahl Hirschman Index of the companies	0.7	0.3	0.3
	Degree of increase in demand	0.3	0.3	0.3
	Technical feasibility and efficiency of substitutions in main applications	0.7	1	1
	Annualised price volatility	0.7	1	1

In addition, economic criteria for lithium are classed as risky. No suitable substitutes for lithium and cobalt can be used in lithium-ion batteries that counteract supply bottlenecks. Market prices are also highly volatile and likewise cause supply uncertainties. By contrast, **lithium-iron-phosphate batteries** do not need any cobalt in their manufacture. They are therefore viewed as an alternative, especially for the electric mobility market and are already used by car brands such as Tesla or BYD.[94]

93 Cf. VDI 4800 Blatt 2:2018-03, p. 64.
94 Cf. Adamas Intelligence (2022).

Lithium mining in Germany[95]

A lithium mine is currently being established in the eastern Erzgebirge region. The deposit discovered is said to contain up to 125,000 tonnes of lithium and is currently the largest deposit in Europe. The amount of lithium thus equates to around 20 million vehicles that can be supplied with batteries.

Thermal sources for electricity and heat production are also a source of lithium at the same time. For this reason, a pilot system for extracting lithium is currently being built in Bruchsal. The brine is rich in lithium, is found at a depth of 2,542 metres and has a temperature of 131 °C. Each litre of brine contains around 150 milligrams of lithium. A technology to extract the lithium from the brine is currently being developed. If it is implemented successfully, around 800 tonnes of lithium could be generated per year. Although this would not cover demand for lithium for the whole of Germany, there are more thermal sources in the North German Basin and the Upper Rhine Graben fault that could be tapped into using this technology.

(b) Availability of End-of-Life Batteries

In accordance with the raw materials criticality according to VDI Guideline 4800, Sheet 2 (cf. Table 7), there is little development of functional end-of-life technologies for lithium and cobalt. These recycling structures and technologies are currently in development. However, these structures need to be upscaled in order to process the numbers of batteries that will be sent for recycling in future (cf. Results of the Technical Discussion, p. 93).

The recycling capacities required are inconsistent with the actual **availability of end-of-life batteries**. This is impaired by various factors (cf. Chapter 4.1.3):

[95] Cf. Kempkens, W. (2021).

- In particular, faulty waste electronic equipment, including installed lithium-ion batteries are **stored in households**. For smartphones, the volume is estimated as more than 200 million old devices[96].

- Small waste electronic devices, including installed lithium-ion batteries are **disposed of in residual waste**. An analysis showed that around 86,000 tonnes of waste electronic equipment per year and an estimated 500 tonnes of secondary batteries end up in residual waste.[97]

- Around three million vehicles are taken off the road in Germany every year. Two thirds of them are **exported abroad** and used again there.[98] This situation will probably be transferred to future scrap electric cars.

- In the medium term, the majority of the estimated quantities of lithium-ion batteries to be recycled are **production waste** that arises from start-up to the safe running of cell production. By definition, these batteries are not end-of-life batteries.[99]

In particular, exports to foreign countries outside Europe represent a loss of resources for the 'battery' value chain. In this respect, more efforts need to be made to keep lithium-ion batteries, in particular, in the substance cycle and make them available to the recycling infrastructure.

[96] Cf. Bitkom e.V. (2021).
[97] Cf. Dornbusch et al. (2020), p. 97.
[98] Cf. Umweltbundesamt (2022b).
[99] Cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), p. 23.

Discussion on the Introduction of a Mandatory Deposit

The European Commission's proposed Battery Directive does not currently contain any requirements for a mandatory battery deposit. This was demanded by the Single Market Committee, but did not receive a majority in the European Parliament,

An upcoming study is therefore to examine the practical implementation options and the benefits of such a deposit on batteries.[100]

A deposit system for batteries entails both advantages and disadvantages. It can improve the return structures and the quantities returned. Fires caused by lithium-ion batteries that have been disposed of incorrectly could thus also be reduced. On the other hand, the bureaucracy may increase and existing return systems could be harmed.

A survey on the subject of deposits on smartphones showed that 53 percent of those questioned in Germany were against such a deposit, while 43 percent were in favour. 19 percent of those questions would not consider returning their own smartphone at all. A large number of those surveyed (45 percent) stated a deposit amount of € 25 as sufficient incentive to return their old mobiles.[101] Another survey showed a more differentiated picture. Among those surveyed, 51 percent found the introduction of a deposit system for smartphone to be very good and 31 percent good. Only eleven percent were against a deposit system in principle.[102]

On the basis of the proposed Battery Directive, there will not initially be any blanket requirements to introduce a battery deposit. However, the feasibility and wisdom of implementation in the future will be examined in further planned studies.

[100] Cf. Umwelt- und Energie Report (2022).
[101] Cf. Bitkom e. V. (2021).
[102] Cf. Jongebloed, K. und Kessens, L. (2021).

(c) Potential Fire Risks for Lithium-Ion Batteries

Lithium-ion batteries can ignite spontaneously under certain conditions. For example, impacts can lead to malfunctions that result in a short circuit and increased heat development. As a result, it is possible for the electrolyte to heat up and evaporate. In turn, this can lead to a typical inflation of lithium-ion batteries and possibly result in ignition with a subsequent explosion. Thermal Runaway is a special form of spontaneous ignition. The battery capacity is released in faulty battery cells in the form of heat. Neighbouring cells are heated in the process and, in turn, contribute to heat development in neighbouring cells. Once started, this process can no longer be interrupted and results in a fire in the entire battery.[103]

Short circuits in lithium-ion batteries often arise from the formation of dendrites on the negative electrode - inter alia, due to charging and discharging the battery. Dendrites form on certain impurities or on structural inhomogenities on the lithium surface and continue to grow and branch out from there[104]. When they reach the opposite electrode, they can cause a short circuit in the presence of the inflammable electrolytes. Consequently, the lithium-ion batteries start to burn.[105] The transport of lithium-ion batteries is therefore classed as **the transport of dangerous goods** because even transport vibrations can lead to damage and consequently cause fires. Therefore, there are fixed demands for such transport in accordance with the European Convention concerning the International Carriage of Dangerous Goods by Road (ADR), which mean extensive, but necessary, bureaucracy for the disposal sector.[106]

[103] Cf. LionCare GmbH (2022).
[104] Cf. Dürfeld, K. (2021).
[105] Cf. Juschkat, K. (2021).
[106] Cf. Stiftung GRS Batterien (2020).

Transport Solutions for Lithium-Ion Batteries

Various solutions are offered for the transport of lithium-ion batteries. They meet statutory requirements and prevent uncontrolled burning of the batteries during storage and transport. For example, containers are characterised by insulation that has a heat-insulating effect and protects against heat, by a seal that prevents liquid penetration from the outside and by inflammable, absorbent padding.[107]

(d) Lack of Sales Markets for Recyclates

Many new innovative recycling methods are being developed. The end products of these recycling methods for batteries and rechargeable batteries that can be sent to the production of more batteries comply with a Battery Grade Material.

Currently, the following materials can be recovered from the recycling processes, as can be seen from Table 8:

Table 8: Materials recovered from Battery Recycling[108]

Company	Recovered Raw Materials	Input
Accurec	Lithium, copper, iron, nickel, cobalt, aluminium, plastic	Li-ion, Ni-Cd, Ni-Mh
Duesenfeld GmbH	Lithium, cobalt, nickel, iron, copper, aluminium,	Li-ion, LFP
Eramet	Lithium, cobalt, nickel, iron, copper, aluminium,	Li-Ion, Alk/Zn-C
Redux	Iron, aluminium, copper, plastic	Li-Ion, Alk/Zn-C

After their hydrometallurgical treatment, the metals are available in the form of sulphates - in other words, as salts. Although other components, in particular the electrolyte solution or separator films, can already be recovered, they are **not present in sufficiently high quantities** to return them to industry. However, talks with manufacturing companies are taking place here as well as general discussions on centralised or decentralised recycling to tap into these flows of recyclables, too.

[107] Cf. Stiftung GRS Batterien (2022).
[108] Cf. Baltac, S. und Slater, S. (2019), p. 37.

(e) Second-Hand Batteries

One major aspect of the use of lithium-ion batteries in e-mobility is their service life and capacity. Depending on the maintenance of the batteries, they can be used for between five and ten years. However, their capacity falls over time. Nevertheless, after being removed from electric vehicles, lithium-ion batteries often **still have more than approx. 80 percent** of their original capacity.

Continuing to use these lithium-ion batteries is therefore an attractive alternative to immediate recycling. Therefore, in recent years more and more projects have been launched that use old vehicle batteries **as energy stores** for example.

In such a case, an industrial electricity store was manufactured completely from old lithium-ion batteries to balance out the peak loads of a disposal company. After being in use for more than 3 years, the pilot system was installed at a new location and there it now optimises a photovoltaic system's own power consumption. In addition to the design and construction of a pilot system, analysis devices have been developed to assess the condition of the old vehicle batteries. A **review of the State of Health** is essential in order to decide on resource-efficient continued use.[109]

3.2 State of the Art

Due to the relevance of lithium-ion batteries in the current context, their recycling routes are discussed below. Recycling measures largely comprise deactivation, dismantling, mechanical reconditioning, pyrometallurgy, hydrometallurgy or pyrolysis and can be arranged in different ways. An overview of possible process variations can be found in Figure 7:[110]

[109] Cf. Saubermacher (2022).
[110] Cf. Doose, S. et al. (2021), p. 3.

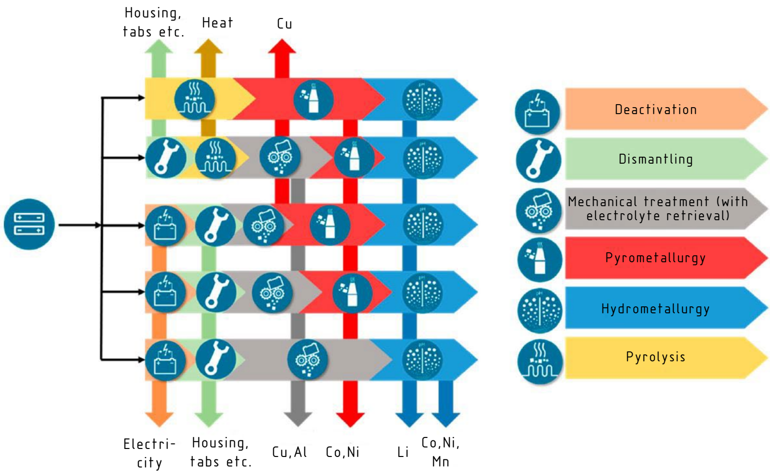


Figure 7: Process Variations Battery Recycling CC BY 4.0 Doose, S. et al.[111]

Deactivation and dismantling of the battery cells is upstream of the various treatment stages. Dismantling is currently still by hand. Due to the increase in cell packs, for example, it is to be assumed that either semi-automatic or fully automatic dismantling plants or full introduction to shredder lines will be more important in the future.[112]

Mechanical reconditioning often comprises a crushing stage (shredders) under vacuum, protective gas atmosphere ($Ar/N_2/CO_2$), in liquid nitrogen or in a water-salt solution. The reason for this stage is the highly reactive components in the batteries. This is usually followed by a vacuum distillation and a dry stage to prepare the electrolyte solution for reuse. In a subsequent mechanical separation, metallic components, such as steel, copper or aluminium, and a mix of electrode materials, binders, additives and residual components of the electrolytes, what is known as the black mass, are separated.[113]

[111] CC BY 4.0 Doose, S. et al. (2021), p. 3.
[112] Cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), p. 28.
[113] Cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), pp. 29f.

After the **pyrometallurgical process** lithium-ion batteries are placed in a smelter plant in which they go through various temperature ranges. The organic components evaporate, whereas the metal compounds are smelted at higher temperatures and the cobalt, nickel and iron compounds are reduced to metals. Organic components and the graphite are oxidised and are lost as materials, but provide thermal energy for the process. Manganese compounds, lithium and aluminium end up in the slag, whereas copper, cobalt, nickel and iron form an alloy. These substances can subsequently be recovered in a hydrometallurgical process.[114]

The **hydrometallurgical or wet chemical process** is designed to separate the substance mixtures that come from the pyrometallurgy and/or the mechanical treatment. This is either the hydrometallurgical separation of copper, nickel and cobalt after the pyrometallurgy or treatment of the black mass. Overall, the process is more ecologically harmless than the pyrometallurgical process because the latter is more energy intensive due to high temperatures and makes exhaust gas cleaning necessary. However, waste water cleaning is absolutely essential in the hydrometallurgical process.[115]

3.3 Innovative Recycling Technologies

The rapid growth of the battery market - especially of lithium-ion batteries - requires a (further) development of lithium-ion battery recycling. The Federal Government's battery research funding promotes this step. The umbrella concept **Forschungsfabrik Batterie [Battery Research Factory]** is a large-scale funding scheme in this context with various elements.[116] This also includes the recycling and green battery skills cluster (greenBatt), which focuses on solution strategies on the challenges in end of life of batteries.[117] Individual developments and innovations (even those independent of the recycling and green batteries skills cluster) are briefly presented below.

[114] Cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), p. 30f.
[115] Cf. Neef, C.; Schmaltz, T. und Thielmann, A. (2021), p. 31f.
[116] Cf. Kompetenznetzwerk Lithium-Ionen-Batterien e. V. (2018).
[117] Cf. greenBatt (2021d).

Here, it must be pointed out that the developments in recycling technologies must always be monitored against the **background of digitisation**. For example, notable research projects such as "Battery Pass"[118] or "CIRPASS"[119] – including in exchange with the Catena X initiative[120] – are currently dealing with the development of prototypes of a **digital product passport**, which should ensure the traceability of batteries and provide important information on the battery along the whole value chain. The aims are optimisation and efficient closure of the entire battery value chain.

3.3.1 Dismantling Batteries and Rechargeable Batteries

Dismantling is the first process stage in substance recovery from lithium-ion batteries in particular. The focus of current studies is on the automated and semi-automated dismantling of battery cells. The **DeMoBat (Industrial Dismantling of Battery Modules and Electric Motors)** research project focuses on the feasibility of "industrial and automated dismantling of battery modules and electric motor aggregates taking account of general economic and regulatory conditions"[121]. The aim of the joint project is to develop four demonstrators.

- Demonstrator 1 is for the validation and illustration of an industrial and (partially) automated dismantling of battery modules from battery systems.
- Demonstrator 2 is for the validation and illustration of an industrial and (partially) automated dismantling of battery cells from battery modules.
- Demonstrator 3 is for the dismantling of individual battery cells and their substance fractioning. In addition, the possibility of reusing the recovered cathode and anode materials in the manufacture of new battery cells is examined.

[118] Cf. The Battery Pass (2022).
[119] Cf. CIRPASS (2023).
[120] Cf. Catena-X (2023).
[121] Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA (2022).

- Demonstrator 4 is for the validation and illustration of an industrial and (partially) automated dismantling of electric motor aggregates[122].

The results and challenges of the project were presented in the technical discussion on “Innovative Recycling Technologies for Industrial Batteries” (cf. Part II of this brief analysis, page 95).

Among other things, the project **DemoSens (Digitisation of an Automated Dismantling and Sensor-Based Mechanical Reconditioning of Lithium-Ion Batteries for High-Quality Recycling)** is looking into the feasibility of an automated, sensor-based and digitised dismantling of lithium-ion batteries. The aim is to develop a robot system as a pilot system that carries out dismantling to the module or cell level and enabled sensor-based material detection and thus sorting into fractions. In this connection, machine learning methods should be developed that ensure independent and self-regulating dismantling. In addition, a comparison of the information from dismantling and subsequent mechanical reconditioning requires an iterative and mutual adaptation of the process stages and thus increases efficiency. Results are expected at the end of the project term on 30.09.2023.[123]

The results – especially from the first project – show the relevance of a **recycling-friendly product design of battery modules**. Ultimately, the current trend towards welded and bonded battery modules makes efficient dismantling more difficult. Added to this is the fact that a large number of battery types are available on the market with different cell shapes and diverse cell chemistry, which also complicates the efficient dismantling of battery modules. The manufacturing companies are required here to think of recycling-friendliness as early as possible during product design.

3.3.2 Recycling Batteries and Rechargeable Batteries

Some market players are already established in battery recycling with their technologies and are also strongly integrated in research activities. The latter underlines the need to develop existing processes further constantly in order

[122] Cf. Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA (2022).
[123] Cf. greenBatt (2023).

to be able to react quickly to rapidly developing cell types and increase the recycling rate.

For example, Accurec Recycling GmbH has been recycling all types of rechargeable batteries for more than 27 years and in 2016 built a new location for the recycling of lithium-ion batteries (annual capacity: approx. 3,000 tonnes per year). There, the batteries are sorted, dismantled and – as required – discharged. The organic components are split and pyrolysed using thermal treatment in a rotary kiln. This process is carried out at max. 600 °C so that base metals, such as aluminium, do not oxidise. In addition, there is waste gas treatment via an afterburner and an extinguishing system, in which, after conversion into high-pressure steam, the excess energy is available for other industrial processes. The subsequent mechanical treatment separates the pyrolysed battery cells over several separation mechanisms into a steel fraction, a copper-aluminium fraction and an electrode powder rich in cobalt and nickel. The products should subsequently be sent on to smelting works and further-processing industries. The process is currently mainly expanded and refined **via research projects**.

Further involvement in research projects also aims at improving the recovery rates of critical elements such as cobalt.[124]

- The one-year **Chemical-Free Lithium Recovery from Lithium-Ion-Based Waste Batteries (CLIMA)** research project aims at the development of innovative extraction and refinery methods for obtaining a high-quality lithium salt with the use of very small quantities of operating materials, which can be sent to cell production as a battery-friendly product.[125] For this purpose, a system for lithium recovery and purification should be built and integrated in the company's process chain.[126]

- The large-scale **"Material-Efficient Recycling for the Circular Economy of Car Stores by means of Technology without Residues" (Mercator)** research project is based on studying a controlled, energy-neutral pyrolysis process and a subsequent hydro-mechanical separation of the

[124] Cf. Sojka, R.; Pan, Q. und Billmann, L. (2020), p. 6.
[125] Cf. Land.NRW (2021), p. 2.
[126] Cf. ACCUREC Recycling GmbH (2022).

secondary raw materials it contains. In this way, lithium is to be recovered and recoverable graphite examined. The aim is to achieve a recycling rate of more than 70 percent here.[127] The project builds upon the results and findings of its predecessor project "**Demonstration Plant for a Cost-Neutral, Resource-Efficient Processing of Worn-out Li-Ion Batteries from Electric Mobility (EcoBatRec)**", in the wake of which, autothermic vacuum pyrolysis for procedures to crush, classify, sift and separate the material fractions was developed.[128]

- The **"First of a kind commercial compact system for the efficient recovery of cobalt designed with novel integrated leading technologies (CROCODILE)"** research project, with a total of 24 project participants, is concerned with the (further) development of a treatment method for resource-critical cobalt (cf. Chapter 3.1.3 (a)). Pyrometallurgical and hydrometallurgical, biological and electrometallurgical technologies are the focus of the research.[129] For example, a pilot system using the solvent extraction method (SX) will transfer cobalt concentrates from the black mass into cobalt salts.[130]

Another company, Duesenfeld GmbH, operates a patented method that achieves a substance **recovery rate of around 91 percent**. The process builds on the results and findings of the **Lithorec I and Lithorec II** research projects and has been transferred into practice as a spin-off. The process starts with a deep discharge. The electricity recovered is used to operate the process machines and is fed into the grid. After an appropriate storage time, it is dismantled with zero potential, in which fractions such as aluminium and copper that are already unmixed are screened out at this stage. Crushing takes place under inert gas (N_2); vacuum drying is with the low-temperature method at a maximum of 50 °C. As a result, no hydrogen fluorides are formed and energy-intensive gas washing can be avoided. The dried battery fragments can then be recovered with the help of various separating mechanisms. These include aluminium, copper, iron, plastic film and the black

[127] Cf. ACCUREC Recycling GmbH (2022).
[128] Cf. Erneuerbar mobil (2022).
[129] Cf. Crocodile Project (2018).
[130] Cf. ACCUREC Recycling GmbH (2022).

mass. Subsequently a hydrometallurgical process – currently still at pilot scale – is run that produces the end products nickel sulphate ($NiSO_4$), cobalt sulphate ($CoSO_4$), manganese sulphate ($MnSO_4$), lithium carbonate (Li_2CO_3) and graphite in battery quality. The method can recycle all types of lithium-ion batteries economically and processes around 500 kilograms of material per hour.[131] Further research and successive upscaling of the hydrometallurgical process are currently in progress. Additional information on the process can be found in the technical discussion “Innovative Recycling Technologies for Industrial Batteries” (cf. Part II of this brief analysis, page 116).

Redux GmbH recycles batteries and has a vision of zero waste for its implementation. With the recovery method, **recovery rates of 95 percent of the metals contained** can currently be achieved. Here, too, the process starts with discharging in which the energy is fed into the grid. Dismantling manually, plastics, cables, electronic components and aluminium are subsequently screened out. The electrolytes and separator are then screened in a thermal treatment. Aluminium arrester films can be recovered with the special procedure. Then, an iron, an aluminium and an aluminium-copper fraction are screened out with the help of a mechanical treatment. The black mass recovered is characterised by a high level of purity and can be sent directly to a hydrometallurgical process.[132] The processes developed are also based on intensive research work. Currently, the company is actively involved in the CROCODILE and “**Future Lithium Ion Battery Recycling for Recovery of Critical Raw Materials (FuLiBatteR)**” research projects. The latter examines the efficient recovery of critical raw materials such as lithium, phosphorous, cobalt, silicon and graphite and the economically relevant metals copper, nickel and manganese.

The examples listed show that recycling lithium-ion batteries is strongly linked to research activities and, in the current context, is linked to a rapid and, above all, necessary further development. Against this background, the **“Demonstration Centre Battery Recycling” project** created the technical and economic design of a recycling centre for lithium-ion batteries including all standard processing stages and the appropriate value chain architecture.

[131] Cf. Duesenfeld GmbH (2022).
[132] Cf. Redux GmbH (2022).

The Demonstration Centre is to take a look at pre-industrial research and help with the generation of necessary procedural knowledge for the further development of the recycling of lithium-ion batteries. Implementation of the **demonstration, testing and research system for battery recycling** is currently at the political discussion stage or in the planning process.[133, 134]

Further activities in the field of the further development of lithium-ion battery recycling are shown in an overview in Table 9. This is merely a small extract from further research projects. Further relevant and interesting projects can be seen on the Recycling & Green Battery skills cluster website and the Battery Forum Germany project database.[135, 136] The diversity of the activities underlines the current technological development potential of battery recycling.

[133] Cf. Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen (2021).
[134] Cf. Land Nordrhein-Westfalen (2022).
[135] Cf. greenBatt (2021f).
[136] Cf. Batterieforum Deutschland (2022).

Table 9: Innovative Developments in Battery Recycling

Project	Brief Explanations on the Content	Source
Graphite recovery by means of foam flotation	At the Helmholtz Centre in Dresden-Rossendorf (HZDR), the recovery of graphite from waste batteries was studied. A concept using the foam flotation method was developed for this. This is an established process for mineral separation from waste rock. Separation features of foam flotation are particle and surface properties such as morphology and size. Since the process takes place using selective hydrophobising, the minerals can thus be removed via the foam due to their hydrophobic properties and the ability to adhere to gas bubbles.[137]	Vanderbruggen, HZDR (2021), Press Release
Recovery of Active Cathode Materials using Froth Flotation	the active cathode materials can be separated by means of a direct form of recycling, in which their electrochemical performance remains. The project studied the use of the foam flotation method to separate untreated lithium nickel manganese cobalt oxide and a lithium manganese oxide. It could be proved that a 95 percent separation of the lithium nickel manganese cobalt oxide and the lithium manganese oxide or the enrichment of this in the foam product was possible through several stages of the separation process. The method is thus an effective and low-cost separation method for the direct recycling of mixed cathode compositions.[138]	Folayan et al. (2021),Energy Technology
Digitisation of Mechanical Sorting Processes in Battery Recycling	After the separation processes, the materials of the lithium-ion batteries are fragments. The project is developing a measuring system to record the properties of the shredded material for every fragment on-line and in-line. In combination with image data (spectroscopic or hyperspectral information), large data sets are thus obtained. Using machine learning, they are to be processed in such a way that engineering connections can be made about the particle type and shape and the composition. The measuring and control system to be developed is to be used along the entire recycling chain for quality monitoring and data acquisition.[139]	GreenBatt (2022), Introduction to the GreenBatt Projects: DIGISORT
Regeneration of lithium manganese oxide cathodes by means of hydrothermal reaction in a solution containing Li	The study shows that a degraded lithium manganese oxide cathode can be regenerated using a hydrothermal reaction in a solution containing lithium. Using this method, it is possible to recreate the stoichiometry and the microphase purity of the cathode material and to use it again in battery manufacture. As part of a life cycle analysis, it was proved that this one-stage regeneration offers ecological and economic advantages over pyrometallurgical and hydrometallurgical processes.[140]	Gao et al. (2020), Applied Materials & Interfaces
Hydrometallurgical Approach for the Complete Recycling of Lithium-Ion Batteries	The project aims to recover lithium from the black mass. To do this, carbon dioxide, which initially binds the lithium into lithium carbonate to release it subsequently from the black mass, is used. In this way, 95 percent of the lithium can be recovered as material suitable for batteries. The remaining metals, such as cobalt, nickel, manganese or copper are leached out chemically and processed into pure chemical compounds.[141]	GreenBatt (2022), Presentation of the Green-Batt Projects, EarLiMet

[137] Cf. Helmholtz-Zentrum Dresden - Rossendorf e. V. (2021).

[138] Cf. Folayan, T.-O. et al. (2021), p. 1.

[139] Cf. greenBatt (2021a).

[140] Cf. Gao, H. et al. (2020), p. 1.

[141] Cf. greenBatt (2021b).

Project	Brief Explanations on the Content	Source
Pyrometallurgical Processing of Entire Battery Cells and Fine Fractions	The objective of the project is to develop a stable process with the fundamental steps of pyrometallurgy - slag processing -, hydrometallurgy to recover lithium from slags containing manganese and materials similar to slag and a slag that can be processed in the construction sector. The subject of the studies is, by way of example, cell generation 6-2-2-NMC. The conditions (fluctuating input mixtures, influence of manganese, for example, pretreatment of the battery cells, properties of the flotation regime, etc.) under which the process runs stably and efficiently are being studied. Finally, there is to be an economic and ecological evaluation of the established process route.[142]	GreenBatt (2022), Presentation of the Green-Batt Projects, PyroLith
Measuring and Identifying Electrolyte Components	The project is developing a method to measure low- and high-boiling components of the electrolyte. With the possibility of this process monitoring or data collection, findings about their whereabouts in the process can be generated. The process strategy building on this, which is to be implemented at laboratory and pilot scale, aims for complete recovery of all components of the electrolyte. Finally, the process engineering effort to separate the electrolyte is to be identified using the results.[143]	GreenBatt(2022), Presentation of the Green-Batt Projects, LOWVOLMON
Development of a Robust Resynthesis Route of Active Materials for Lithium-Ion Batteries	Building on the findings of other projects in the Recycling & Green Battery skills cluster, such as EarLiMet, PyroLith or LOWVOLMON, a catalogue of requirements is to be drawn up for recyclate raw materials. For this, the usability of extracted materials in resynthesis (e.g., influence of impurities in the black mass on use as new in battery production) is to be studied and appropriate requirements derived for industrial use.[144]	GreenBatt (2022), Presentation of the Green-Batt Projects, EVanBatter
Development of an Industrial Processing Technology	The project contained the development of an industrial processing technology. The focus of the research was on the reuse and recycling of the cathode and anode materials. To do this, processes for dismantling and processing while avoiding high-temperature methods were studied. Processed cathode and anode materials were also tested for their usability in small- and large-format test cells and a corresponding electrochemical characterisation was undertaken. The suitability of the method was reviewed in a demonstration line.[145]	Battery Forum Germany (2021), Project Database, ReALBatt

[142] Cf. greenBatt (2021g).
[143] Cf. greenBatt (2021e).
[144] Cf. greenBatt (2021c).
[145] Cf. Batterieforum Deutschland (2018).

4 WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT

4.1 Challenges in the Recycling of Waste Electrical and Electronic Equipment

In 2020, around 2.8 million tonnes of electrical and electronic equipment (EEE) were put into circulation in Germany. Depending on the devices' useful lives and the unclarified whereabouts of the waste equipment outside the official disposal structure, just under 45 percent of the EEE has been collected and sent for recovery every year in recent years. However, there is no comprehensive recovery for some of the special and precious metals they contain - above all, the rare earths. This leads to the loss of precious, limited resources.

4.1.1 Current Recycling Situation

The German Electrical and Electronic Equipment Act (ElektroG) lays down that after 2019 the amount of waste equipment collected must be 65 percent of the average amount of electrical and electronic equipment put into circulation in the three preceding years. In 2020, **the collection rate was 44.1 percent** and therefore clearly failed to meet the statutory collection rate (approx. 20 percentage points or 490,000 tonnes; cf. Table 10).[146]

Table 10: Volume of Electrical and Electronic Equipment and Collected EEE

	2017	2018	2019	2020
Quantities put into circulation	2,081,223 t	2,375,643 t	2,590,244 t	2,847,926 t
Quantities Collected	836,907 t	853,124 t	947,067 t	1,037,019 t
Collection Rate	45.1%	43.1%	44.3%	44.1%
Amounts lacking for the collection rate of 65%	-	-	442,818 t	489,855 t

The waste electrical and electronic equipment collected is to be sent for recovery, which comprises preparation for reuse, substance recycling or recovery as energy. For this, recovery rates – for the six specified equipment categories – are defined by the ElektroG.

[146] Cf. Umweltbundesamt (2022c).

For preparation for reuse (PfRU) and recycling, depending on the equipment category, 55 to 80 percent of the EEE collected should be reused or recycled. All of these rates were met (cf. Table 11).

Table 11: Recovery Rate PfRU and Recycling[147]

No.	Equipment Category	Preparation for Reuse	Recycling	Rate PfRU + Rec
1	Heat transfer systems	255 t	162,383 t	85.4%
2	Screens > 100 cm²	1,866 t	100,759 t	90.5%
3	Lamps	No information	6,939 t	93.1%
4a	Large appliances, with the exception of PV modules	6,475 t	258,076 t	88.9%
4b	PV modules (Chapter 5)	No information	14,155 t	91.9%
5	Small appliances (external dimension < 50 cm)	6,955 t	232,333 t	82.5%
6	Small IT and communications devices (external dimension < 50 cm)	1,655 t	107,436 t	89.2%

4.1.2 Statutory Challenges

The German Electrical and Electronic Equipment Act (ElektroG)[148] governs the return and the proper disposal of electrical and electronic equipment and transposes the European requirements of the WEEE directive[149] (Directive 2012/19/EU on waste electrical and electronic equipment (WEEE)) into national law. Currently, the European Commission is carrying out soundings on a planned **revision of the European WEEE Directive**. European players in the value chain were able to give feedback on the planned evaluation of the directive until 3 November 2022. Within the scope of this planned evaluation, the European Commission is to examine in greater detail the following aspects, which represent **challenges** for the member states and players in the value chain in the transposition of the WEEE Directive into national law:

- **Achieving targets** for the collection of waste electrical and electronic equipment

[147] Cf. Umweltbundesamt (2022c).
[148] Cf. Bundesrepublik Deutschland (2015).
[149] Cf. 2012/19/EU:2012-07.

- Guaranteeing **proper treatment** of waste electrical and electronic equipment and the associated same competitive conditions
- Application of the requirements to **extended manufacturer responsibility** (especially to online sales)
- Combating **illegal activities** and practices not meeting the standard in the entire process of management of waste electrical and electronic equipment

The umbrella recycling association EuRIC spoke in favour of further demands for a **harmonisation** of the rules for all players in the European value chain. Currently, the European requirements are being adopted in national statutory regulations. Lack of harmonisation between the EU states is one of the reasons why less than 40 percent of the waste electrical and electronic equipment in Europe is recycled.[150] In this connection, other players have spoken in favour of the transfer of the Directive into a Regulation so that it enters into force directly, is more legally binding and ensures harmonised legislation in the entire European Union.[151] VERE e. V. also criticises the lack of harmonisation, for example viewing comparability of European collection rates critically because different calculation methods and different data are used as a basis in each case.[152] The association also speaks in favour of a **product-group-specific sustainability strategy** or a differentiation of waste electrical and electronic equipment according to the raw materials potential in each case. VERE e. V. argues that this would comply with the aims of the European Green Deal. It would also be sensible to deploy the defined ecodesign criteria more specifically in order to achieve a fundamental change in dealings with electrical equipment. The WEEE legislation was supposed to lay down **binding product and information requirements** for log life, repairability, reusability, recyclability, proportion of recycled materials and reduction of the environmental impacts during production, use and disposal. According to Deutsche Umwelthilfe this would have a positive impact on the

[150] Cf. EuRIC (2022).
[151] Cf. Deutsche Umwelthilfe (2022).
[152] Cf. VERE e.V. (2022).

useful life of electrical and electronic products that, as a key elements, reduces the environmental impact of resource consumption and disposal due to longer lives.[153] In addition, it is proposed to introduce a **digital product passport** for electrical and electronic equipment that provides detailed product information about the raw materials installed and ecological and social impacts of the product for users and waste management. This and other feedback, comments and notes are currently being collected and evaluated. Acceptance by the European Commission is expected before the end of 2023.

4.1.3 Challenges in Practice

Since the first version of the ElektroG became effective in 2005, successive adaptations have been made to the collection and treatment of waste equipment. For example, in the most recent revision electronic marketplaces and fulfilment service providers were also required to control the proper registration of manufacturers without headquarters in Germany. In this way, it can be ensured that they assume the statutory product responsibility for equipment put into circulation in Germany by them. Nevertheless, in spite of every effort, the target collection rate of 65 percent is clearly missed.

Collection of Waste Electrical and Electronic Equipment

The recording and collection of waste electrical and electronic equipment has been comprehensively implemented all over Germany. Nevertheless, for many years the sufficiently well-known problem of insufficient collection quantities and therefore missing secondary raw materials has resulted in extensive discussions. In addition to other causes (cf. Chapter 5.1.2), various studies identify the following reasons:

(a) Storage of waste equipment in households

German households are a **sink for waste electrical and electronic equipment**. Resource-relevant waste equipment, such as laptops and mobile phones have been and still are being stored in households. According to a survey from 2018, there were around **32 million** old, unused notebooks and computers in German households. The stored quantity of unused laptops and

[153] Cf. Deutsche Umwelthilfe (2022).

PCs has thus increased by around ten million in comparison to 2014 with a stored quantity of 22 million items.[154] There was a similar development for mobile phones. In German households in 2021 there were therefore around **206 million old mobiles**. That is around 100 million additional mobiles in comparison to a survey from 2015.[155] On average, a tonne of mobiles contains around 250 grams of gold.[156] With an assumed average weight of 170 grams per mobile, that equals a total storage quantity of around nine tonnes of gold. For comparison: a tonne of gold ore contains approx. five grams of gold. That equals around 1.8 million tonnes of mined gold ore and clearly illustrates the resource relevance of stored waste electrical and electronic equipment.

(b) Disposal of Waste Electrical and Electronic Equipment in Household Waste

According to estimates, the annual amount of waste electrical and electronic equipment (this includes small appliances such as toasters, printers, electrical and electronic toys, etc.) **disposed of in household waste** is around 86,000 tonnes.[157] In spite of information on users keeping them separate on the electrical and electronic equipment, these items disposed of incorrectly are as yet unavoidable.

[154] Cf. bvse (2019).
[155] Cf. Bitkom e.V. (2021).
[156] Cf. Umweltbundesamt (2022d).
[157] Cf. Umweltbundesamt (2022a).

(c) Illegal Shipments of Waste Electrical and Electronic Equipment

As part of a study, it was estimated that, in 2008, around **155,000 tonnes of waste electrical and electronic equipment** were shipped abroad via the Port of Hamburg.[158] The majority of this equipment was disposed of incorrectly, mostly by means of incineration on landfills in order to exploit the substances. WEEEs are also shipped over the eastern European borders. The amount is estimated to be approx. 77,000 tonnes per year.[159] The legislator has now reacted to illegal shipments. Only checked and working used equipment protected against damage by adequate packaging may now be exported as "non-waste". Moreover, a reverse burden of proof has been agreed. This means that transport companies who convey declared used goods must prove that the functioning equipment is intended for further use. Previously the burden of proof lay on the side of the authorities who had to prove a violation of the German Waste Shipment Act (AbfVerbrG).[160] There are no current studies on illegal shipments that are still in progress.

(d) Calculating the Collection Rates

In addition to logistic reasons, another reason for the gap between the quantity put into circulation and the quantity collected was identified in the calculation methodology used as a basis. The useful life of electrical and electronic equipment ranges from several months to several years or even decades. Considering the continuous increase in equipment put into circulation, which is growing more quickly than the WEEs available for collection, **the calculation methodology distorts** the resulting collection rates. For this reason, some players are in favour of a collection rate per head (person) and year.[161, 162]

Preparation for Reuse

In the Federal Government's Coalition Agreement 2021 – 2025 it was laid down that a **right to repair** was to be implemented. As a starting point and

[158] Cf. Sander, K. und Schilling, S. (2010), p. 57.
[159] Cf. Janz, A. et al. (2009), pp. 17f.
[160] Cf. BMUV (2022a).
[161] Cf. European Recycling Platform (2022), p. 1.
[162] Cf. EWRN (2022), p. 5.

basis for the implementation of this, ecological product design is cited on the one hand, on the other the law on the sale of goods and financial support.[163] However, this approach can be implemented only if the necessary conditions are met by manufacturers and parties putting the products into circulation for repairability, availability of spare parts and repair information. In this connection, the Round Table on ‘Repair’ published thirteen recommendations, which included EU-wide and cross-product-group repair requirements, financial support for the production of spare parts or provision of a software update over a period of ten years.[164] In this connection, a study from the Federal Environment Agency examined and presented factors that encourage a repair of electrical and electronic equipment and ultimately can be laid down as demands of manufacturers and communicated to customers via relevant labelling[165].

Recovering Precious and Special Metals

With mixing with less resource-relevant substance flows such as printers, copiers, etc., many precious and special metals can no longer be recovered from the resultant sorting fractions. Although an optimisation of the shredder and sorting technology is possible and sensible, there should be a **manual dismantling of components** such as circuit boards before shredding for even more efficient raw material recovery. Concentration of the especially valuable substance flows (precious and special metals) thus optimises the yield in the recovery process, especially with resource-relevant electrical and electronic equipment, which are often characterised by a dissipative distribution of the raw materials in the equipment, i,e, they are distributed in small quantities throughout the entire product. Due to the current market situation, this work stage is sometimes already implemented in this way, however further optimisation potential has been identified here.[166] In this connection, the Federal Environment Agency has commissioned studies whose results will be applied in the Waste Equipment Treatment Ordinance.

---

[163] Cf. BMUV (2022b).
[164] Cf. Meyer, K. (2022).
[165] Cf. Ritthoff, M. et al.(2022), p. 15.
[166] Cf. Umweltbundesamt (2022d).

Optimisation of the recovery of special and precious metals was highlighted by a recent study. The average useful life of 61 metals was studied in a life cycle analysis. It was shown that for 15 of the metals studied (including gallium, scandium or germanium) the production losses were greatest, for three metals (barium, mercury, strontium) the usage loss and in the case of the remaining 43 metals the losses **following waste management or recycling**; this includes metals such as aluminium, zinc, silicon, silver and gold and many more.[167]

Another study examined the **status of metal recovery methods** from post-consumer waste products. Among other things, it could be seen that in particular technologies for rare earths are still in pilot system status or laboratory scale (cf. Table 12).

Table 12: Status of Recovery Technologies for Metals from Post-Consumer Waste Products[168]

Recovery Chains on Industrial Scale	Recovery Chains in Pilot Plants	Recovery Chains on Laboratory Scale
Silver, Gold, Cobalt, Iridium, Lithium, Osmium, Palladium, Platinum, Rhodium, Ruthenium, Antimony, Tin, Tellurium	Indium, Cerium, Lanthanum, Neodymium, Praseodymium, (Cerium and lanthanum from NiMH batteries)	Cerium, Dysprosium, Gallium, Terbium, Beryllium, Germanium, Niobium, Rhenium, Tantalum, Tungsten, (Cerium, Terbium from fluorescent lamps)

For this reason, improvement of the circular economy for most metals should take effect mainly in the area of developing recyclable products with longer useful lives and in optimised recovery from dated applications with the help of improved collection and recycling systems.[169]

[167] Cf. Charpentier Poncelet, A. et al. (2022), p. 722.

[168] Cf. Sander, K. et al. (2018), p. 92.

[169] Cf. Charpentier Poncelet, A. et al. (2022), p. 717.

Dialogue Platform Recycling Raw Materials[170]

As part of the Federal Government's raw materials strategy from 2020, it was decided in a dialogue process between industry, academia and the administration to successively improve supply security with the help of the contribution of secondary raw materials. For this, barriers and weaknesses were to be identified with the participating players in two working groups (WG Metals and WG Industrial Minerals) and - building on this - substance-flow-specific target parameters laid down and possible conflicts of objectives identified. As a result, options for action are derived by means of which both new recycling potentials of the individual substance flows and the system as a whole can be tapped into. The results of the work of the Dialogue Platform Recycling Raw Materials are expected in autumn 2023.

4.2 State of the Art

Following collection and recording of the waste electrical and electronic equipment, before recovery it must be subjected to first treatment in accordance with article 3 number 24 ElektroG. This is where waste equipment is either separated for preparation for reuse or pollutants are removed so that recyclables can subsequently be removed from the waste equipment (in this connection, particular attention should be paid to the complete removal of batteries and rechargeable batteries, cf. Chapter 3 of this brief analysis).[171] The subsequent mechanical treatment of waste electrical and electronic equipment can be schematically broken down into three basic steps of conditioning, classification and sorting (cf. Figure 8) before metallurgical final processing is carried out. The steps from collection and mechanical treatment until precious metal recovery intermesh and are carried out by various players. Great efficiency for every process stage is essential to achieve high recovery rates and generate an efficient overall system.[172]

[170] Cf. Dialogplattform Recyclingrohstoffe (2022).
[171] Cf. Hofmann, A. (2017), p. 70.
[172] Cf. Hagelüken, C. (2022), p. 14.

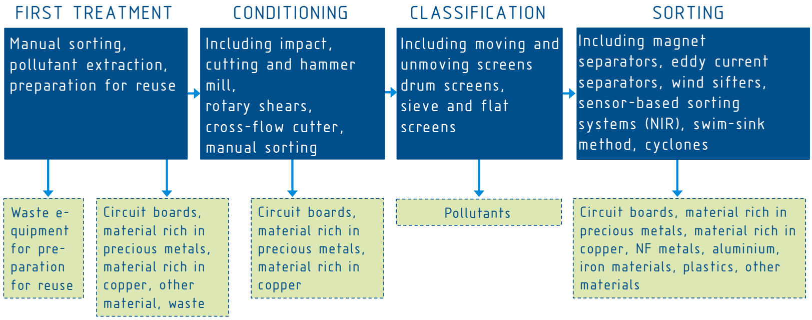


Figure 8: Schematic Mechanical Treatment of Waste Electrical and Electronic Equipment (own figure)[173]

The **mechanical treatment** of waste electrical and electronic equipment differs depending on the equipment category concerned (cf. Table 11). For example, the requirements for the recycling of heat transfer systems or cold reservoirs (equipment category 1) are different (focus on removing pollutants) from those, for example, for small appliances or IT communications devices. Requirements for the treatment of waste electrical and electronic equipment are laid down in the WEEE Treatment Ordinance and the LAGA Notification 31b "Technical Requirements for the Treatment and Recovery of Waste Electrical and Electronic Equipment".[174]

In the following, the focus is on mechanical treatment of **resource-relevant waste electrical and electronic equipment**, in particular the equipment categories 6 (small IT and communications devices) and 4a (large appliances without PV modules). The installed circuit boards play a major role in both of these categories. Depending on the type of device, the metal concentration in the circuit boards can be between 1 and 50,000 mg per kg of circuit board.[175] Therefore, according to the WEEE Treatment Ordinance, devices with particularly high levels of recyclables in circuit boards (regarding the treatment method) should be separated as early as the first treatment. In

[173] Own figure based on Martens, H. und Goldmann, D. (2016), p. 459.
[174] Cf. Hofmann, A. (2018).
[175] Cf. Sander, K. et al. (2018), p. 82.

particular, this concerns laptops, mobile phones, servers, routers, etc.[176] In addition to early separation of circuit boards,

- a complete steering of fractions containing precious metals to precious metal recovery,
- recovery of circuit board fractions and fractions containing precious metals according to the state of the art and
- separation of components containing special metals and sending them to metal recovery should also be ensured (cf. Figure 9).[177]

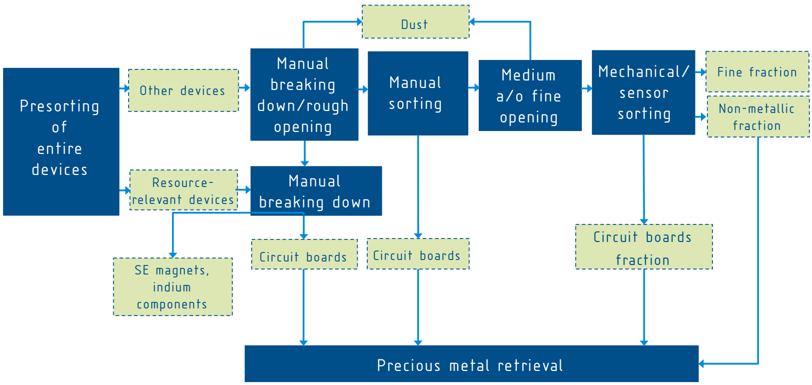


Figure 9: Recovery of Circuit Boards (own figure)[178]

Precious metals are recovered subsequently by a combination of **mechanical, pyrometallurgical and hydrometallurgical processes**. A distinction is made between three main routes: the route for iron/steel, the aluminium route and the route for copper/precious metal/several special metals. In addition, there are specialised metallurgical processes for rare earths from magnets or indium from LCD screens.[179] Companies such as Aurubis or Umicore operate special processes that perform efficient recovery of the mass

[176] Cf. Kummer, S. et al. (2020), p. 32.
[177] Cf. Kummer, S. et al. (2020), p. 32.
[178] Own figure based on Kummer, S. et al. (2020), p. 32.
[179] Cf. Hagelüken, C. (2022), p.15.

metals such as copper, as well as precious and special metals such as gold.[180, 181] What is key here is that a carryover of precious and special metals in particular to other substance flows, such as plastics, iron/steel or aluminium, is prevented because recovery would no longer be possible in that case. More detailed information on the recycling technologies applied on an industrial scale can be found in the established literature.

4.3 Innovative Recycling Technologies

The focus of current projects in the field of recycling waste electrical and electronic equipment is on efficient and effective dismantling and separation of the main resource-relevant components within mechanical treatment - this is what is known as inverse production. The research and development work is therefore responding to the demands to avoid carryover of substance flows.

Therefore, in the project "**ADIR – Next generation urban mining – Automated disassembly, separation and recovery of valuable materials from electronic equipment", an automated dismantling system has been developed for** mobile telephones and circuit boards that achieves efficient detachment of valuable materials with the help of laser systems, robotics, vision systems and information technologies. The focus is placed on the elements tantalum, neodymium, tungsten, cobalt and gallium. For example, up to 96 - 98 percent of the tantalum was recovered. In the pre-competitive project, more than 1,000 mobile phones and more than 800 large computer circuit boards and the process data was collected in a database to be used for future planned optimisations, for example, in process acceleration and automation. In addition, employees should be enabled to train the recycling plant to new mobile phone models. According to the authors, great interest was expressed by industry because the valuable materials can be removed efficiently using the process and, at the same time, it is economically feasible.

The similarly designed IRETA project developed three methods that build on each other to recover tantalum from electronic scrap.

180 Aurubis AG (2022).
181 Umicore Precious Metals Refining (2022).

(1) Detection and laser removal of tantalum capacitors

(2) Mechanical treatment for obtaining tantalum anodes

(3) Process for cleaning the anodes to obtain pure tantalum

It could be shown that tantalum with a purity degree of 98 percent could be recovered across the process chain. Since purities of 99.5 percent are required for the sale of pure tantalum, the method is to be further optimised with more research, although the authors believe that this can be done. In addition, ecological advantages in every environmental category are achieved for all three methods - compared with the use of primary tantalum. However, the methods developed have not yet proved to be economic. This is due to the colourfulness of the tantalum capacitors. Whereas, for example, yellow capacitors can be easily separated, a lower detection rate was achieved for black tantalum capacitors, which account for around half of the capacitors. The follow-on **IRETA 2 project deals with ecological and economic optimisation and transfers the results into a system concept**.[182]

The **iRVE** project aimed to develop methods for the effective recovery of valuable materials from large quantities of electrical and electronic scrap. It was to identify which method - selective dismemberment or dismemberment using selective crushing and sorting - delivers the more efficient separation results. Selective dismemberment is the detection of features, such as size and colour of circuit boards, by sensor systems and the targeted identification and dismemberment of the components. Dismemberment by means of selective crushing and sorting comprises electrohydraulic crushing by means of which the circuit board components are separated and subsequently sorted automatically. With the help of these results, companies should be enabled to optimise existing plants or design new plants, especially in the field of the detection, sorting and separation of materials[183, 184]

The Irish company Votechnik has developed the automated recycling system ALR-400 for the efficient dismantling of LCD screens. The central element of

[182] Cf. Sauer et al. (2019), pp. 219ff.
[183] Cf. Bayerisches Staatsministerium für Umwelt und Verbraucherschutz (2022).
[184] Cf. Technische Hochschule Aschaffenburg (2022).

the system is the KR Quantec industrial robot from Kuka. The industrial robot itself is characterised by high operational efficiency and a modular structure, whereby the maintenance work is minimised and the robot is 90 percent recyclable. In turn, the ALR-400 recycling system allows automated dismantling of LCD screens. This means that on the one hand gases such as mercury and sharp-edged components can be removed without risk to employees and, on the other hand, the LCD screens can be efficiently broken down into the relevant substance flows. Moreover, due to automation, dismantling is quicker: whereas around five devices can be dismantled per hour by hand, automated sorting enables the dismantling of approx. 60 devices per hour.[185]

A new concept that is still in the early research and development phase is biodismantling. A research project studied the efficient separation of circuit board components by placing the boards in an iron solution bath. At the start, a mixed culture of various bacteria, in particular acidthiobacillus ferrooxidans, is added to this solution. As a result, there is an oxidation of Fe II to Fe III since the added bacteria use the Fe II as an energy source. Full oxidation is completed after approx. two days. The circuit boards are then placed in the solution. The Fe III works as a strong oxidising agent, dissolves the soldering tin and following this is reduced to Fe II again. Thus, after approx. 20 days, the components fall off the circuit board and can be recycled. Bioleaching is still at the research stage and entails long dwell times, is however deemed to be a method for targeted substance flow generation that saves resources and energy.[186]

[185] Cf. KUKA Deutschland GmbH (2022).
[186] Cf. Monneron-Enaud, B. und Kramer, J. (2021), p. 1.

5 PHOTOVOLTAIC MODULES

5.1 Challenges in Recycling PV Modules

Photovoltaic modules have been experiencing constant growth since the 1990s. The number in circulation once again leapt up with the entry into force of the Renewable Energies Act in 2000. In 2020, just under two million photovoltaic systems with a capacity of 54 Gigawatts were installed. That equates to electricity generation of approx. 51.4 Terawatt hours.[187] By 2040 it is estimated that the installed capacity will more than treble.[188] The useful life of the modules is approx. 25 years. Currently, the returns from the useful phase are still manageable. Nevertheless, the disposal and recycling sector will have to deal with a rising substance flow of PV modules in the future.

5.1.1 Current Recycling Situation

For example, since 2015 manufacturers and retailers who put solar or PV modules on the German market have had to register with the Stiftung ear (electrical and electronic Equipment register foundation) in line with the Waste Electrical and Electronic Equipment Act (ElektroG). Quantity registrations and proofs of disposal, etc. must be documented by authorised third parties in line with the requirements of the Stiftung ear. This means that the manufacturers and retailers meet the **product responsibility**requirements laid down in article 23 of the Circular Economy Act.

The amounts reported have been recorded since 2016. The data comprise the **quantities put into circulation** and the quantities accepted in a first treatment system. The quantities put into circulation increased by approx. 60,000 tonnes annually from 2017 to 2019 and for 2019 totalled **272,422 tonnes** (cf. Table 13).

[187] Cf. EU-Recycling Magazin (2022a).
[188] Cf. Wirth, H. (2022), p. 6.

Table 13: Quantities of Photovoltaic Modules Put into Circulation[189, 190, 191]

Year	Quantity of PV Modules Put into Circulation
2019	272,422 tonnes
2018	211,142 tonnes
2017	155,539 tonnes

The quantities sent for **first treatment** recorded a marked increase from 2,000 tonnes in 2016 to more than **15,000 tonnes** in 2020 (cf. Table 14). The number of disposal plants that accept PV modules also increased, from 13 plants in 2016 to 27 plants in 2020.[192]

The majority of PV waste that reached disposal in 2018 was damaged, either during production, transport, installation, due to inexpert dismantling or the influence of weather (for example hail) or had been taken out of service – based on guarantee or warranty cases.[193] In future, it is to be assumed that the **quantities for recovery will rise**, because the first installed models from the 1990s will successively reach their technical end of life. Up to 2020, around three quarters of the disposed PV modules came from commercial use. For example, they are PV modules that had been installed on production sites and similar commercial facilities.

Table 14: Quantity Development of PV Modules (2017 – 2020)[194]

Year	Quantity Total	Of which Commercial Waste Equipment	PfRU*	Material recovery	Energy recovery	Removal
2020	15,400 t	11,000 t	No information	11,900 t	1,100 t	No information
2019	13,400 t	10,800 t	No information	11,500 t	1,200 t	No information
2018	7,900 t	5,600 t	900 t	6,000 t	800 t	200 t
2017	3,600 t	2,600 t	300 t	3,100 t	200 t	No information
2016	2,000 t	No information	400 t	1,300 t	200 t	100 t

*Preparation for Reuse

[189] Cf. Löhle, S.; Schmiedel, U. und Bartnik, S. (2019), p. 14.
[190] Cf. Löhle, S.; Schmiedel, U. und Bartnik, S. (2020), p. 68.
[191] Cf. Umweltbundesamt (2022c).
[192] Cf. Statistisches Bundesamt (2022b).
[193] Cf. Hofmann, A. (2018), p. 68.
[194] Cf. Statistisches Bundesamt (2022b).

There are three generations of PV modules, in which **currently only the first and second generation** are of relevance in the disposal sector.

- 1st generation: PV modules with solar cells made of crystalline silicon (c-Si)
- 2nd generation: PV modules with thin-layer cells made of amorphous silicon (a-Si), cadmium telluride (CdTe) or cells containing copper, indium, selenium or sometimes gallium (CIS, CIGS)
- 3rd generation: Other technologies, such as organic PV modules[195]

Of the PV modules currently installed, around 90 percent are assigned to the first generation, whereas around ten percent are accounted for by PV modules with thin-layer cells (2nd generation). Third generation technologies are currently mostly in development and negligible for return and recycling.

5.1.2 Statutory Challenges

With the exception of PV modules in the statutory framework of the ElektroG, the modules – together with the other categories of waste electrical and electronic equipment – are subject to **a total collection rate to be achieved of 45 percent** by 2018. This is calculated on the basis of the ratio of the collected weight of waste electrical and electronic equipment to the average total weight of the electrical and electronic equipment put into circulation in the last three years.

In 2018, the collection rate for waste electrical and electronic equipment was 43.11 percent, thus falling just below the statutory target of 45 percent. The long useful life of PV modules and the large quantities put onto the market greatly influence the collection rate. Without consideration of PV modules, a collection rate of 44.69 percent would have been achievable for 2018. This situation also makes reaching the **collection rate of 65 percent set since 2019 even more difficult**. This collection rate for 2019 of 44.3 percent fell well below the statutory target of 65 percent. An adjusted and harmonised

[195] Cf. Hofmann, A. (2017), p. 29.

calculation basis of the collection rates has already been addressed by comments within the context of the soundings for a planned revision of the European WEEE Directive.[196]

The discrepancy between the PV modules put into circulation and the PV modules collected and sent for recovery is due to the technical useful life on the one hand and, on the other, the economic running of PV modules. The latter is largely influenced by the **feed-in tariff laid down in the Renewable Energies Act**. Owners of plants are guaranteed remuneration over a period of 20 years. In 2000 this was still 50 cents per kilowatt-hour for small arrays. Since 2022, this has been 6.83 cents per kilowatt-hour - justified by the sliding scale laid out in the Renewable Energies Act. This means that, as the feed-in tariff is progressively reduced, economic operation of PV systems is thrown into question and may have an impact on the quantities put into circulation in future.

5.1.3 Challenges in Practice

It is to be assumed that the PV modules to be disposed of will increase in the years ahead. It is predicted that the waste volume of PV modules will be around 14,000 – 22,000 tonnes in 2025, which will increase continuously in subsequent years to around 4.9 to 9.6 million tonnes in 2050 (cf. Table 15). Other estimates, however, assume a volume of around 37,000 tonnes in 2022 and 87,000 tonnes by 2030.[197]

Table 15: Prediction of PV Module Quantities for Disposal by 2050[198]

Year	Predicted Quantity
2025	14,000 – 22,000 tonnes
2030	152,000 – 223,000 tonnes
2035	1.8 – 2.9 million tonnes
2050	4.9 – 9.6 million tonnes

The PV modules are **largely made of glass, plastic and aluminium**. Materials that are installed in smaller quantities include copper, silicon or other

[196] Cf. European Commission - Have your say (2023).
[197] Cf. Kummer, S. et al. (2020), p. 116.
[198] Cf. Kummer, S. et al. (2020), p. 116.

metals, such as zinc, nickel, selenium, lead and cadmium. In particular, cadmium telluride thin-layer modules have an especially high proportion of glass at more than 95 percent (cf. Figure 10).[199]

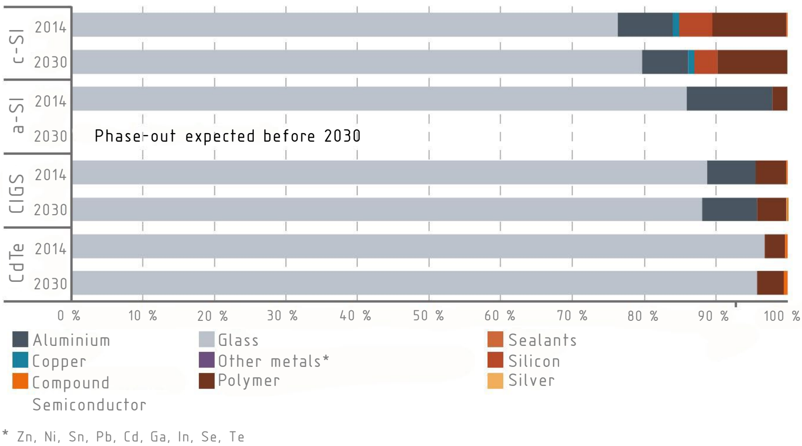


Figure 10: Composition of PV Modules of the Various Generations © IRENA and IEA-PVPS[200]

In retrospect, it has been determined that the glass waste potential for all PV technologies in 2020 was between 8,000 and 51,500 tonnes. For aluminium, the calculated waste potentials for the same year amount to approx. 7,000 to 41,000 tonnes, in which only c-SI modules were considered here.[201]

The adequate **recycling of PV modules** contributes greatly to the **reduction of greenhouse gas emissions**. For example, the recycling of one tonne of PV modules with a silicon basis saves around 800 to 1,200 kg CO_{2eq} due to the reuse of the recyclates. The credits here are mainly achieved by recycling the glass and aluminium fraction.[202]

[199] Cf. IRENA und IEA-PVPS (2016), p. 41.
[200] © IRENA und IEA-PVPS (2016), p. 41.
[201] Cf. Kummer, S. et al. (2020), p. 128.
[202] Cf. Fraunhofer IBP (2012), p. 2.

After recovery, the **high-quality glass of the PV modules** is used in the manufacture of thermal/sound insulation, glass wool or cellular glass and is thus **downcycled**.[203] However, use in the sheet and container glass industry is technically possible in principle. Metal particles, film residues, etc. can already be separated successfully from silicon-based PV modules. However, economic implementation is not yet realisable due to the small quantities for recovery at the moment.[204]

The aluminium frame of the PV modules is either dismantled as standard before crushing or recovered after the shredder process. Passing on to high-quality material **aluminium recycling** is established and generates the **highest yields** from PV recycling.

Other elements of PV modules are **critical raw materials** such as silicon, indium, gallium and silver. Currently, none of these substances are recovered. Technical methods for recovery have already been developed that, however, are **not (yet) economical** because of the small quantities for PV modules for recovery.[205]

5.2 State of the Art

A standardised recovery of PV modules can only be roughly derived due to the **great variety of treatment technologies**. The methods range from dissolving in organic solvents, ultrasound radiation using pyrolysis trough conveyor belt kilns and fluidised bed reactors up to wet- and dry-mechanical treatment or for chemical etching.[206] The following deliberations on the State of the Art are therefore based on the “Technical Requirements for the Treatment and Recovery of Waste Electrical and Electronic Equipment” from the notifications of the Federation/Länder Working Group on Waste (LAGA) 31 B.[207]

Before PV modules can be recovered as substances, the module types are sorted. Thick-layer modules (1st generation, c-Si modules) and thin-layer

[203] Cf. Wolf, J.; Brüning, R.; Nellesen, L. und Schiemann, J. (2017), pp. 166ff.
[204] Cf. Kummer, S. et al. (2020), p. 129.
[205] Cf. Kummer, S. et al. (2020), pp. 133ff.
[206] Cf. EU-Recycling Magazin (2022a).
[207] Hofmann, A. (2018).

modules (2nd generation, for example CdTe modules) and silicon- and non-silicon-based PV modules are to be separated from each other. Adequate separation is possible only by labelling the PV modules and by specialist staff using data sheets. Separation on the basis of visual features of the PV modules can lead to unsafe results.[208]

Then, the frame or the back rail (fitting rails bonded to the rear), the junction box and cables are **dismantled** before the PV modules can be sent to the appropriate recovery process.

Silicon-based thick-layer (c-Si) and sometimes also thin-layer modules (a-Si) can be recovered together using mechanical treatment methods. Experiments have shown that a separation of monocrystalline and polycrystalline PV modules (1st generation) has no influence on recyclability. This is influenced by the manufacture-specific design of the PV modules.[209] The mechanical treatment comprises conditioning, classification and sorting in principle (cf. Figure 11).

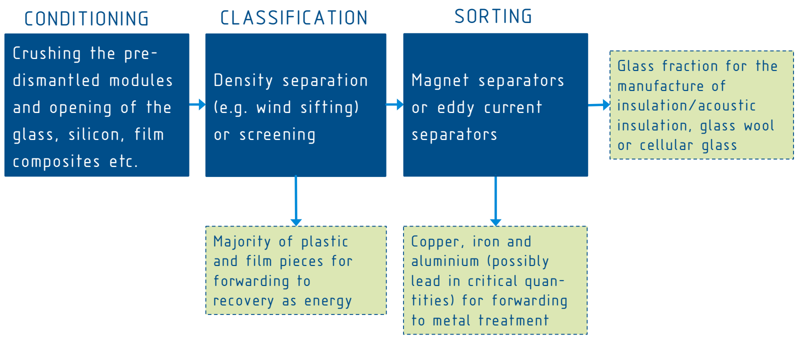


Figure 11: Mechanical Treatment of Silicon-Based PV-Modules (own figure)[210]

[208] Cf. Hofmann, A. (2018), p. 71.
[209] Cf. Pohl, R. und Heitmann, B. (2019), p. 21.
[210] Own figure based on Hofmann, A. (2018), pp. 71f.

Thin-layer modules can be recycled in three stages due to plastic lamination:[211]

(1) (partial) delamination of PV modules by means of physical crushing (shredding, milling), by chemical or thermal breakdown of the encapsulation film or by cold grinding

(2) Removal of glass coating (shards or intact substrate) and separation of non-metallic fraction (encapsulation film, glass) from the metallic fraction (semiconductors, metals)

(3) Reclamation and Refinement of Elements

Further methods are still at the development stage. In this connection, it is required for the recycling of PV modules to be legally tied to **realistic, but ambitious recycling rates**, especially to establish high-quality closed cycles from glass, aluminium and critical metals such as indium, gallium, etc. in future.[212]

5.3 Innovative Recycling Technologies for PV Modules

Great variety can be seen in practice, research and development and in pilot projects on recovery technologies for PV modules.[213]

An established process is the recycling method for **CdTe thin-layer modules** of one company. It accepts return of modules it has manufactured and recycles them. After crushing (delamination), the thin layer is dissolved with sulphuric acid and hydrogen peroxide in a stainless steel drum (removal of the glass coating). The glass fraction and the film are screened out, whereas the metals in the remaining liquid are precipitated in a subsequent process. Tellurium and cadmium are recovered from the remaining filter cake, in which the tellurium is reused for the production of PV modules (Reclamation

[211] Cf. Marwede, M. (2013), p. 26f.
[212] Cf. Deutsche Umwelthilfe e.V. (2021), p. 11.
[213] Cf. EU-Recycling Magazin (2022a).

and Refinement of the Elements). The glass fraction is then sent to glass recycling, while the plastic fraction is used for the manufacture of RFDs.[214]

Another **patented recycling method for CdTe/Cds thin-layer modules** is operated by Antec GmbH, which accepts the return of PV modules free of charge. Here, the thin-layer modules are physically broken down into module fragments. They are then exposed to an atmosphere containing oxygen at temperatures of at least 300°C in order to split the ethylene-vinyl-acetate layers. After pyrolysis, the module fragments go through an etching process (gas atmosphere containing chlorine at a temperature of more than 400°C), in which $CdCl_2$ and $TeCl_4$ are formed, which are then condensed and liquefied again by means of cooling.[215] According to information from the operating body, the method can use nearly all of the raw materials obtained for the manufacture of new thin-layer modules.[216]

The company and process developer LuxChemtech GmbH received the KfW Award in 2022. This is based on technological developments by means of which the silicon and other semiconductor materials can be recycled and returned to the cycle.[217] In the final analysis, crushed silicon pieces are heated to 1,500°C in a special mould, melted down and then slowly cooled from bottom to top ensuring even crystallisation. After a process time of five days, a 900 kilogram **silicon block in primary ware quality** is available for new production.[218] The company is also one of 13 participants in the EU **"Photorama"** project (PHOtovoltaic waste management – advanced Technologies for recOvery & recycling of secondary RAw MAterials from end-of-life modules). The aim of the project running to 2024 is to develop a reliable PV recycling technology. For this, a pilot system is to be developed that can demonstrate a TRL 7.

The "**ReProSolar**" project has total funding of € 4.8 million from EIT RawMaterials and aims to develop a highly efficient method for the recycling of waste PV modules. In this way, all of the components of the PV modules are

[214] Cf. Hofmann, A. (2017), p. 73.
[215] Cf. Tao, J. und Yu, S. (2015), p. 114.
[216] Cf. Antec Solar GmbH (2022).
[217] Cf. Vallero, C. (2022).
[218] Cf. Vallero, C. (2022).

to be fully recovered and pure silicon, silver and glass returned to industry. For this, a new delamination technology separates the solar cells from the glass sheet efficiently in order to recover the materials using innovative physical and chemical methods without having to crush the PV modules. Its feasibility on an industrial scale is being tested by the cooperation partners FLAXRES GmbH in Dresden and ROSI Solar in Grenoble, so that by 2023 it will be possible to process around 5,000 tonnes of waste PV modules per year in a demonstration system.[219]

FLAXRES GmbH has developed a technology that breaks down PV modules into their components in a few seconds by means of a **highly intensive light pulse**. Highly intensive light is shone onto the PV modules and converted into heat by the light-absorbing layer, such as silicon wafers. With fast heating of the materials, the bond can be efficiently separated without the use of chemicals. This results in the unmixed separated fractions of glass, aluminium, plastic, silicon with silver, cables, electricity busbars and junction boxes. The technology is installed in mobile containers and can therefore be used directly on site.[220]

ROSI Solar GmbH is a start-up, which recycles PV modules with physical, thermal and gentle chemical processes, i.e., without the use of aggressive chemistry. In raw materials recovery, the focus is on both the silicon and the silver from the wires that collect the electricity generated and conduct it through the panel. According to information from manufacture, the **silver can be almost completely recovered in a solid form**. The silicon is recovered in pure form and is available for use for the production of new PV modules.[221]

Rinovasol has, among other things, specialised in the **refurbishing of solar modules**. Damage to solar and photovoltaic panels is sometimes reconditioned on site; panels that cannot be refurbished are sent for recycling, in which according to information from the company, up to 100 percent of the

[219] Cf. Evonik Industries AG (2021).
[220] Cf. FLAXRES GmbH (2022).
[221] Cf. ROSI SAS (2022).

components can be recycled.[222] The technological recycling process developed comprises releasing the individual components of a PV- module and sorting the pure material fractions and is usually carried out by the local cooperation on site using mobile breakdown units.[223]

Another breakdown technology has been developed by Impulstec GmbH.[224] Using the **shockwave crushing plant** EHF 400, the bonded material is separated in a reactor. The shock waves that are generated electrically separate front glass, the EVA coating and the silicon layers from each other. Per hour, between 75 and 200 kilograms of PV module material can be treated and recovery rates in the amount of three percent achieved for silicon, one percent for copper and seven to eight percent for the EVA coating.[225]

In addition, a working group at the Fraunhofer Centre for Silicon Photovoltaics CSP together with Reiling GmbH & Co. KG has developed a **scalable recycling process** which makes the recycling of all crystalline silicon PV modules possible – irrespective of the origin of the modules. For this, glass and plastic are removed from PV module pieces of a size of approx. 0.1 to one millimetre (from mechanical breakdown) following various separation processes. By means of subsequent wet-chemical etching, the rear contacts, the silver contacts, the anti-reflection layers and the emitters can gradually be removed. The product is a purified silicon, which can be further processed into monocrystalline or quasi-monocrystalline ingots and used for new wafer production. The PERC modules[226] manufactured at the Fraunhofer ISE from fully recycled silicon have an efficiency rate of 19.7 percent. They are therefore below premium PERC solar cells, which have an efficiency rate of 22.2 percent, but still have a higher efficiency rate than old, worn out modules.[227]

[222] Cf. EU-Recycling Magazin (2022a).
[223] Cf. RINOVASOL (2022).
[224] Cf. impulstec (2022).
[225] Cf. EU-Recycling Magazin (2022a).
[226] PERC solar cells (Passivated Emitter and Rear Cell) are characterised by the fact that they absorb the light better using optimised solar cell rear sides and therefore have higher efficiency. – Cf. energie-experten.org (2022).
[227] Cf. Fraunhofer-Institut für Solare Energiesysteme ISE (2022).

6 SUMMARY AND OUTLOOK

Recycling is a key strategy for closing cycles, using raw materials efficiently and protecting limited resources. Due to the legal enshrining of the circular economy in the German Circular Economy Act, recycling is assigned to German waste management. Looking at the circular economy in the broader sense, alongside reuse, repair or remanufacturing, it is an instrument that helps to close material cycles, taking account of ecological criteria (for example, toxicity, the use of energy, etc.).

This process is already working for some fractions, such as glass and aluminium. At the same time, the recycling industry is facing various challenges – especially with respect to the fractions plastics, batteries and rechargeable batteries, waste electrical and electronic equipment or PV modules – ranging from heterogenic substance flows and a lack of product information, such as the distribution of raw materials in the product, right up to the marketing of low-quality recyclates.

For the fractions considered in the brief analysis, it has been shown that innovative technological developments are responding to the existing challenges. The further development of efficient separation technologies, especially in the field of waste electrical and electronic equipment, so that resources in the substance flow can be separated efficiently for further treatment should be highlighted here. New sorting technologies, such as the watermark for plastics, can create new incentives for the efficient closing of substance cycles. The rising quantity of PV modules and lithium-ion batteries also shows that new recycling capacities are needed to ensure that important raw materials remain in the German or European economic cycle and achieve independence or at least a certain degree of resilience in the face of the global raw materials markets.

A key prerequisite for this are closed processes that harmonise with each other along the value chain. From the point of view of the circular economy, in addition to the substance flow-specific, i.e., unmixed collection of the substance flows as far as possible, in particular recycling-friendly product design and provision of information concerning the installed materials and components are essential for efficiently implementing the goals of circular management and recycling processes. The following therefore applies to a resource-efficient circular economy: overall efficiency is the sum of the efficiencies of the individual stages of the value chain.

Following on from the many discussions on designing a resource-efficient circular economy, it is increasingly clear that the recycling sector has been set technical limits with respect to the closed loop management of raw materials. Ultimately, recycling processes can only work as efficiently as the preconditions allow that have already been set by the product design or the manufacture of the products.

A resource-efficient circular economy therefore requires the participation of all players to increase total efficiency. First dialogue processes, such as that on the VDI White Paper[228], the Dialogue Platform on Recycling Raw Materials[229] or initiatives such as the Forum Recyclate[230] are necessary to link the value chain stages, gain an understanding for the processes that take place in it and establish a transparent cycle. This is the responsibility of all players involved in the cycle, because "in order to achieve a real further development we have to think beyond the German Circular Economy Act of the transformation of industrial processes into a circular economy is to succeed"[231].

At political level, in the Coalition Contract it was stipulated that existing raw materials political strategies will be bundled into a "National Circular Economy Strategy".[232] In addition to further ambitions, in particular, the long-lasting, reusable, recyclable and, where possible, repairable design of products is to be encouraged, thus promoting the idea of a resource-efficient circular economy.

[228] Cf. VDI e.V. (2022).
[229] Cf. Dialogue Platform Recycling Raw Materials (2022).
[230] Cf. Forum Recyclate (2022).
[231] Cf. Gosten, A. (2022), p. 4.
[232] Cf. Bundesregierung der Bundesrepublik Deutschland (2021), p. 42.

PART 2: EXPERT TALK

7 RESULTS OF THE EXPERT TALK

7.1 Programme of the Expert Talk

Moderation:	Dr Martin Vogt, Managing Director, VDI Centre for Resource Efficiency
Item 1	**Recycling of Lithium-Ion Batteries: Opportunities and Challenges for Europe**
	Dr Christoph Neef, Fraunhofer-Institut für System- und Innovationsforschung (ISI)
Item 2	**The Problem of Lithium-Ion Battery Recovery**
	Georgios Chryssos, GRS Batterien
Item 3	**Discussion Part I**
Item 4	**Environmentally Friendly Recycling of Lithium-Ion Batteries**
	Julius Schumacher, Duesenfeld GmbH
Item 5	**Industrial Dismantling of Battery Modules and E-Motors: DeMoBat**
	Eduard Gerlitz, Karlsruher Institut für Technologie (KIT), wbk Institut für Produktionstechnik
Item 6	**Discussion Part II**

7.2 Introduction

On 24 February 2022 there was a technical discussion on the subject of “Innovative Recycling Technologies and Industrial Batteries” with 16 participants from research, industry, politics and technical networks. The event was organised by the VDI Centre for Resource Efficiency. The participants in the technical discussion debated which challenges the players in the “Industrial Batteries” value chain would have to face to successfully implement the necessary upscaling of the recycling capacities primarily of lithium-ion batteries.

Article 3 para. 5 of the German Batteries Act is used to classify the term of industrial battery. Accordingly, industrial batteries are defined as batteries that are used exclusively for industrial, commercial or agricultural purposes, for electric vehicles of any kind or for the propulsion of hybrid vehicles specified.

7.3 Volume Development of the New Industrial Batteries

At the start of the technical discussion, it was first of all outlined that high two-digit growth rates for the battery market in Europe are to be expected, especially due to electric mobility as a key driver. Not least, this concerns the new industrial batteries for currently strongly rising production capacities in Europe. Among other things, it was noted that rejects are caused when starting up and establishing the processes, even before steady production is achieved. These spillage rates can amount to up to 50 percent of the plant output and already account for a large proportion of the industrial batteries to be recycled. And this production waste will continue to influence the quantities for recycling in future.

Other large quantities of new batteries come from imports from Asia and represent a resource import that is not to be ignored for the European market. The value chain process for industrial batteries still contains gaps. The shipping of end-of-life vehicles to countries outside Europe has been a well-known problem for decades. Because of this, it is assumed that the shipping of end-of-life electric vehicles will establish itself in the same way. In turn, this process means a loss of resources for Europe. At this point, all of the participants therefore see an acute need for action to keep the urgently needed raw materials in the European value chain – including against the current political background.

Lithium-ion batteries account for approx. 40 percent of new batteries put into circulation and will continue to be the dominant battery technology in the next ten years. This is backed up by the investments currently made in new production facilities, because a commitment to cellular chemistry can already be seen in system planning. A subsequent switch is not only technically complex, but also extremely expensive.

Other battery types, such as sodium and solid state batteries will also be subject to further development, but they will play a subordinate role in comparison to lithium-ion batteries. However, it must be pointed out that, especially because of current rapid developments in electrochemistry, long-term developments are hard to predict.

7.4 Regulatory Developments for Industrial Batteries

The fast-growing, as well as the volume of new industrial batteries already on the market therefore require the creation and establishment of a functioning recycling infrastructure. The European Commission's regulation proposal that encompasses the value chain is a reaction to the corresponding market developments and stipulates that there is to be an obligation to recycling from 2022.

Following on from this obligation, recycling efficiencies (recovery rates from substance recovery) were laid down that amount to 98 percent for copper, cobalt and nickel by 2030 and 90 percent for lithium. With respect to the leap from 95 percent from 2026 to 98 percent from 2030 for the metals cobalt, copper and nickel , it was stipulated that the current technological innovations can certainly achieve this adaptation.

In addition, the use of recyclates from old batteries in new batteries will be mandatory in order to progress the successive development of a recycling market. In this connection, it is noted that adherence to the recycling rates from 2030 demanded by the regulations is unclear. Several reasons were cited for this:

- Since recycling will not be in competition with the primary mining of lithium in particular and also technical limitations limit the amount and quality of recyclates, it is estimated that a maximum recyclate use of five percent coming from waste batteries is to be expected. Any recyclate rates that go beyond this may jeopardise the product quality. Other secondary raw material flows from other industries will have to be used. This step seems possible for nickel, cobalt and copper, but is proving problematic in the case of lithium.

- Furthermore, currently established recycling capacities that recover the above-mentioned rejects must be assigned to the recycling processes close to production. However, these rejects are not counted as end-of-life batteries and cannot therefore be included in the recycling rates to be achieved.

- The useful life of industrial batteries is on average 15 years and can actually be extended if used industrial batteries are transferred to a second-life application. As a result the availability of industrial batteries for the recycling market is delayed. It was pointed out that this longer availability, however, should not be in competition to new business models (for example, "Use instead of Own"), which have an equally positive impact on the useful life and the circular economy. Industrial batteries should therefore be integrated in the establishment of such business models.

- The location of the recycling is not limited to Europe in line with the proposed regulation. This results in the challenge of creating appropriate incentives to keep the industrial batteries and the resources they contain permanently in the European market.

Against the background of the shipping of end-of-life electric vehicles, the availability of secured quantities of end-of-life batteries is assessed as critical by the players. However, the problems cited are taken into account in the drawing up of a valid calculation method for recycling rates in the European Commission's proposed regulation. A revision of the directive is planned for 2027 which will include any adjustments to the specification of the recycling rates. Nevertheless, the high recycling rates are to work as a political signal and create appropriate incentives for the development of innovative recycling processes for batteries.

7.5 Developments of the Recycling Market

7.5.1 Development of Recycling Capacities

The development of the recycling market for batteries is currently very dynamic. The industry is constantly announcing the establishment of new recycling capacities. The installed processes are also very diverse in their design and therefore difficult to compare with each other. It was therefore only roughly estimated that the recycling capacities of around 33 kilotonnes in August 2021 more than doubled to around 72 kilotonnes in February 2022. It was noted here that currently a recycling capacity of approx. 40 kilotonnes is available because some market participants are included in the recycling capacities but they actually carry out no high-quality recycling of batteries. For example, these include scrap dealers who only separate worn out batteries from the housing. Furthermore, technologies newly introduced to the market are viewed critically with respect to upscaling. The feasibility and efficiency can be tested here by means of testing and demonstration centres.

7.5.2 Development of Recycling Quantities and Composition

The available and planned recycling capacities are currently not (yet) sufficient to deal with the rapidly growing quantities of industrial batteries to be recycled (including all production waste or rejects). It is also estimated that by 2025 approx. 100 kilotonnes and by 2030 just under 250 kilotonnes will have to be recovered every year. Partnerships between recyclers and cell manufacturers have already been established for production waste in particular. Here, it is however still open whether and how these structures develop further in future. Cooperations that build upon cycles close to production therefore make sense because - unlike end-of-life batteries - production waste or production rejects are available unmixed and less contaminated. In addition, it was pointed out that the industrial batteries value chain has a global structure. Efficient and sustainable dealings with the value chain structure require interlinking with Asian markets in particular. Since the recycling market is still very young, the scope for action here is not very great.

The composition of the entire substance flow of the battery residues will change over time. The recycling flow currently mainly contains batteries from small applications, which will be replaced by production waste or rejects in the medium term. In the long term, batteries from electric vehicles will dominate the flow of valuable materials. It must be stated here that the efficiency of the recycling processes depends on the battery types to be recycled. Valuable materials obtained from high-quality lithium-ion batteries, such as copper, cobalt, nickel and manganese, allow economic operation. The contents of lithium-iron phosphate batteries (LFP), by contrast, are of lower value and make economic recycling more difficult. From today's point of view, there are therefore no adequate recovery capacities for LFP batteries. At this point it must be stated that the recycling processes presented by Duesenfeld GmbH in the technical discussion includes LFP batteries in recovery as well as high-quality batteries. In addition, existing needs for research into economic LFP recovery were addressed using ongoing projects.

From the point of view of resource efficiency, the status of the delivered batteries offers potential for saving materials and energy. According to the assessment, a considerable portion of the lithium-ion batteries could be sent for a second-life use. However, these batteries (including rejects) do not meet the OEM (Original Equipment Manufacturer) volume production standard and are therefore not approved for second life by them. Moreover, product liability for second-life batteries is often a subject of discussion. It was suggested in this regard that the guarantee should be borne by the operator and not the OEM. However, implementation in practice often leads to legal uncertainties.

7.5.3 Estimating the Need for Investment

The estimated investment costs for a hydrometallurgical process with an exemplary design and a hot process currently lie at around three to four million Euros per kilotonne of batteries and year. The individual players in the "Industrial Batteries" value chain estimate the initial investment required differently. The operators and the OEMs expect annual initial investments to achieve the required recycling capacity of approx. € 2.7 billion, whereas machinery and system constructors expect costs of around € 5 billion until

2040. The investment for the recycling capacities required can be estimated in this range.

7.5.4 Innovative Recycling Technologies

One of the participants presented the innovative process for recycling lithium-ion batteries of all types (NMC, NCA, LFP, LCO, LMO, LTO) of Duesenfeld GmbH. The advantages lie in greater recycling efficiency and a low-energy process due to dispensing with high-energy thermal recovery. In this way, energy-intensive and expensive process components, such as the gas washers to eliminate hydrogen fluorides (HF) can be dispensed with, the licensing cost is reduced and an easily scalable technology is offered.

The treatment process is upstream of dismantling, which is currently done by hand. However, the way of processing the batteries supplied is changing successively, with the bonding or welding of Dell2pack batteries, in particular, making dismantling by hand uneconomical. In future, the dismantling process will be supplemented with a shredder unit here.

The contribution presented by the research results of the DeMoBat project provided the same results. The project studied the automated dismantling of industrial batteries. It was stipulated that the fundamental architecture of the design will not change, but the type of processing makes resource-efficient dismantling more difficult. Recycling-friendly design would lead to more resource-efficient recycling here. This responsibility lies with the OEMs, who, in turn, can make demands for recyclability. In this respect, however, no conditions have to be adhered to so that it is foreseeable no efforts have to be made by the OEM for reasons of economic efficiency. However, this may change as raw material availability reduces.

In the view of the participants, the recycling process should therefore be designed with the highest possible degree of flexibility so that it can respond as quickly as possible to changing battery design and changing cellular chemistry. As has already been stated, the diversity of industrial battery types available on the market is enormous and a flexible recycling process is therefore necessary to close the value chain cycle as efficiently as possible. It would be helpful here to receive information on the structure and the material composition, especially the electrolytes, in the form of QR codes or a way to read out the batteries. This would enable more efficient design of the recycling process (for example, batch processing of the electrolytes) and increase the amount of recyclates that can be achieved. However, from the point of view of the OEMs, issuing such information is difficult and not common currently.

7.5.5 Use of Secondary Raw Materials from Battery Recycling

The recycling infrastructure for batteries is young and means that some of the quantities of potential recyclates currently produced are still too low to find customers on the market. One example is the market for recoverable electrolytes or solvent mixes. The quantities generated are currently too low for reuse in primary battery production. In the case of electrolytes, there is also the problem that they are tailored precisely to the cellular chemistry of the original battery. It is therefore equally difficult at the moment to use the recovered solvent mixes for the manufacture of primary batteries. They are currently sent for thermal recovery. However, research projects are successively addressing this subject.

7.6 Summary

The value chain for industrial batteries is characterised by dynamic growth. Both the production capacities of new batteries and the recycling capacities are constantly being expanded. The regulatory marginal conditions are sending out important signals and reacting appropriately early to the developing market. The exact interpretation of recycling rates in particular is subject to various uncertainties, which are however addressed by a planned revision.

The development of innovative technologies is also extremely dynamic. On the one hand, good practice examples, such as the recycling process of Duesenfeld GmbH, identify the opportunities and potentials of a value chain for industrial batteries run in a cycle and, on the other, reveal the challenges that still have to be mastered. Research projects, such as the DeMoBat project, are helpful here because such project reveal the need to establish a recycling-friendly design for increased resource efficiency and make dismantling and recycling processes as flexible as possible in order to be able to react quickly and adequately to the variety of industrial batteries.

BIBLIOGRAPHY

2012/19/EU:2012-07: Europäisches Parlament und Europäischer Rat, Richtlinie 2012/19/EU des Europäischen Parlaments und des Rates vom 4. Juli 2012 über Elektro- und Elektronik-AltgeräteText von Bedeutung für den EWR, Amtsblatt der Europäischen Union, Straßburg.

ACCUREC Recycling GmbH (2022): Forschung & Entwicklung [online]. ACCUREC Recycling GmbH [retrieved on: 28.10.2022], available at: https://accurec.de/forschung-und-entwicklung

Adamas Intelligence (2022): Passenger EV Battery Chemistries: LFP for the Massive, NCM for the Majority [online], 12.12.2022 [retrieved on: 20.02.2023], available at: https://www.adamasintel.com/lfp-for-the-massive-ncm-for-the-majority/

AIM - European Brands Association (2021): Pioneering Digital Watermarks | Holy Grail 2.0 [online]. AIM - European Brands Association [retrieved on: 26.10.2022], available at: https://www.digitalwatermarks.eu/

Antec Solar GmbH (2022): Garantie & Recycling [online]. Antec Solar GmbH [retrieved on: 02.12.2022], available at: https://www.antec-solar.de/solarservice/garantie-and-recycling/

APK AG (2022): Newcycling® - wie aus Verpackungsabfällen hochwertige Kunststoffgranulate werden [online]. APK AG, 07.06.2021 [retrieved on: 26.10.2022], available at: https://www.apk-ag.de/newcycling/prozess/

Arkin, C.; Caterbow, A.; Chemnitz, C.; Duran, C.; Feit, S.; Fernandez, M.; Flood, C.; Fuhr, L.; Grimberg, E.; Gürtler, S.; Guerrero, L.; Hausmann, J.; von, H.; Kallee, U.; Keith, C.; Knoblauch, D.; Lauwigi, C.; Mederake, L.; Moun, D.; Muffett, C.; Patton, J.; Rehmer, C.; Schächtele, K.; Seeger, D.; Speranskaya, O.; Tat, E. und Ziebarth, N. (2021): Plastikatlas – Daten und Fakten über eine Welt voller Kunststoff. 6. Auflage. Heinrich-Böll-Stiftung; Bund für Umwelt und Naturschutz Deutschland, Berlin.

Aurubis AG (2022): Technologie des Recyclings [online]. Aurubis AG, 01.12.2022 [retrieved on: 02.12.2022], available at: https://www.aurubis.com/produkte/recycling/Technologie

Baltac, S. und Slater, S. (2019): Batteries on wheels: the role of battery electric cars in the EU power system and beyond. Element Energy, London [retrieved on: 28.10.2022], available at: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2019/06/Element_Energy_Batteries_on_wheels_Public-report_4th-June-2019.pdf

Batterieforum Deutschland (2018): ReALBatt - Projektdatenbank [online]. Kompetenznetzwerk Lithium-Ionen-Batterien e. V. [retrieved on: 31.10.2022], available at: https://db.batterieforum-deutschland.de/verbund-projekte/realbatt/

Batterieforum Deutschland (2022): Projektdatenbank [online]. Kompetenznetzwerk Lithium-Ionen-Batterien e. V. [retrieved on: 28.10.2022], available at: https://www.batterieforum-deutschland.de/projektdatenbank/

Bayerisches Staatsministerium für Umwelt und Verbraucherschutz (2022): Innovative Recyclingverfahren für Elektroschrott [online] – Teilprojekt 10: IRVE. Bayerisches Staatsministerium für Umwelt und Verbraucherschutz [retrieved on: 02.12.2022], available at: https://www.stmuv.bayern.de/themen/ressourcenschutz/forcycle/forcycle2/teilprojekt_10.htm

Bechlarz, D. (2022): Enzymatische PET-Bio-Recycling-Anlage in Frankreich geplant. In: plastverarbeiter [retrieved on: 26.10.2022], available at: https://www.plastverarbeiter.de/markt/enzymatische-pet-bio-recycling-anlage-in-frankreich-geplant-439.html

Bitkom e.V. (2021): Mehr als 200 Millionen Alt-Handys lagern in deutschen Wohnungen [online]. Bitkom e.V. [retrieved on: 27.10.2022], available at: https://www.bitkom.org/Presse/Presseinformation/Mehr-als-200-Millionen-Alt-Handys-lagern-in-deutschen-Wohnungen

Bittner, A.; Flegler, A.; Neef, C.; Rostek, L.; Stijepic, D.; Tercero E-spinoza, L. A. und Thielmann, A. (2021): Quantifizierung Batterierecycling Kurzversion. Fraunhofer ISI, Karlsruhe.

BMUV (2018): Bundesumweltministerin Schulze legt 5-Punkte-Plan für weniger Plastik und mehr Recycling vor - BMUV-Pressemitteilung [online]. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz, 30.09.2021 [retrieved on: 24.10.2022], available at: https://www.bmuv.de/pressemitteilung/bundesumweltministerin-schulze-legt-5-punkte-plan-fuer-weniger-plastik-und-mehr-recycling-vor

BMUV (2022a): Das Elektro- und Elektronikgerätegesetz (ElektroG) - FAQ [online]. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz [retrieved on: 08.12.2022], available at: https://www.bmuv.de/faqs/elektronikgeraetegesetz-elektrog

BMUV (2022b): FAQ Recht auf Reparatur [online]. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz, 15.08.2022 [retrieved on: 08.12.2022], available at: https://www.bmuv.de/themen/nachhaltigkeit-digitalisierung/konsum-und-produkte/faq-recht-auf-reparatur

Borealisgroup (2023): Borealis und TOMRA eröffnen hochmoderne Pilotanlage für Kunststoff-Rezyklat - Borealis [online], 21.02.2023 [retrieved on: 21.02.2023], available at: https://www.borealisgroup.com/news/borealis-und-tomra-er%C3%B6ffnen-hochmoderne-pilotanlage-f%C3%BCr-kunststoff-rezyklat

Brunn, M. (2021): Standard-NIR Technologie erkennt Marker. In: Recycling magazin [retrieved on: 26.10.2022], available at: https://www.recyclingmagazin.de/2021/09/08/standard-nir-technologie-erkennt-marker/?msclkid=f335385dd10f11ecacb53f69792b4046

Bundesanstalt für Geowissenschaften und Rohstoffe (2021): Lieferketten und Abbaubedinungen im artisanalen Kobalt-Kupfersektor der DR Kongo. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover [retrieved on: 27.10.2022], available at: https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Downloads/lieferketten_abbaubedingungen_artisanaler_Cu-Co-Sektor_DR_Kongo_de.html

Bundesregierung der Bundesrepublik Deutschland (2020): Deutsches Ressourceneffizienzprogramm III 2020 – 2023 Programm zur nachhaltigen Nutzung und zum Schutz der natürlichen Ressourcen – ProgRess III [retrieved on: 24.06.2020], available at: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Ressourceneffizienz/progress_iii_programm_bf.pdf

Bundesregierung der Bundesrepublik Deutschland (2021): Koalitionsvertrag der Ampel-Koalition aus SPD, Grüne und FDP für die Wahlperiode 2021–2025 – Mehr Fortschritt wagen. Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit. Bundesregierung der Bundesrepublik Deutschland, Berlin [retrieved on: 31.10.2022], available at: https://www.bundesregierung.de/breg-de/service/gesetzesvorhaben/koalitionsvertrag-2021-1990800

Bundesrepublik Deutschland (2015): Gesetz über das Inverkehrbringen, die Rücknahme und die umweltverträgliche Entsorgung von Elektro- und Elektronikgeräten – ElektroG [retrieved on: 08.12.2022], available at: https://www.gesetze-im-internet.de/elektrog_2015/

Bundestag der Bundesrepublik Deutschland (2020): Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen – Kreislaufwirtschaftsgesetz KrWG [retrieved on: 29.04.2021], available at: http://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl120s2232.pdf

bvse (2019): 32 Millionen Elektro-Altgeräte in deutschen Haushalten [online]. bvse-Fachverband Schrott, E-Schrott und Kfz-Recycling [retrieved on: 08.12.2022], available at: https://www.bvse.de/schrott-elektronikgeraete-recycling/nachrichten-schrott-eschrott-kfz/3990-32-millionen-elektro-altgeraete-in-deutschen-haushalten.html

Catena-X (2023): Catena-X Automotive Network | Catena-X [online], 21.02.2023 [retrieved on: 21.02.2023], available at: https://catena-x.net/de/

Charpentier Poncelet, A.; Helbig, C.; Loubet, P.; Beylot, A.; Muller, S.; Villeneuve, J.; Laratte, B.; Thorenz, A.; Tuma, A. und Sonnemann, G. (2022): Losses and lifetimes of metals in the economy. In: Nature Sustainability, 5 (8), S. 717–726. Nature Sustainability. doi:10.1038/s41893-022-00895-8

CIRPASS (21.02.2023): CIRPASS – Digital Product Passport [online], 21.02.2023 [retrieved on: 21.02.2023], available at: https://cirpassproject.eu/

Crocodile Project (2018): First of a kind commercial Compact system for the efficient Recovery OfCObalt Designed with novel Integrated LEading technologies – Recovering Cobalt [online]. Crocodile Project [retrieved on: 03.11.2022], available at: https://h2020-crocodile.eu/

Der Tagesspiegel (2022): Export von Abfall: Deutschland schickt deutlich weniger Plastikmüll ins Ausland [online]. In: Der Tagesspiegel, 2022 [retrieved on: 24.10.2022], available at: https://www.tagesspiegel.de/politik/deutschland-schickt-deutlich-weniger-plastikmull-ins-ausland-6596410.html

Deutsche Umwelthilfe (2022): Position on Waste electrical and electronic equipment – evaluating the EU rules – Position Paper of Environmental Action Germany (DUH). Deutsche Umwelthilfe e.V., Radolfzell [retrieved on: 08.12.2022], available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13420-Elektro-und-Elektronik-Altgerate-Bewertung-der-EU-Vorschriften/F3353321_de

Deutsche Umwelthilfe e. V. (2021): Weißbuch zur Stärkung der Wiederverwendung und des Recyclings von Photovoltaik-Modulen. Deutsche Umwelthilfe e.V., Radolfzell [retrieved on: 21.10.2022], available at: https://www.duh.de/fileadmin/user_upload/download/Pressemitteilungen/Kreislaufwirtschaft/210310_Wei%C3%9Fbuch_Kreislaufwirtschaft_Solarmodule_st%C3%A4rken_DEU_FINAL.pdf

DGAW – Deutsche Gesellschaft für Abfallwirtschaft e. V. (2021): Höhere Rezyklatqualität durch neue Sortiertechnologien? DGAW – Deutsche Gesellschaft für Abfallwirtschaft e.V, Berlin [retrieved on: 26.10.2022], available at: https://www.dgaw.de/fileadmin/Presse_und_Stellungnahmen/PM_Sortiertechnologien_final.pdf

Digital Watermarks (2022): Validation of second prototype machine takes HolyGrail 2.0 one step closer to industrial scale [online]. AIM - European Brands Association, 15.06.2022 [retrieved on: 26.10.2022], available at: https://www.digitalwatermarks.eu/post/validation-of-second-prototype-machine-takes-holygrail-2-0-one-step-closer-to-industrial-scale

Dialogplattform Recyclingrohstoffe (2022): Die Dialogplattform Recyclingrohstoffe [online]. Bundesanstalt für Geowissenschaften und Rohstoffe [retrieved on: 08.12.2022], available at: https://www.recyclingrohstoffe-dialog.de/Recyclingrohstoffe/DE/Home/recyclingrohstoffe_node.html

DIN e. V. (2021): Schub fürs Kunststoff-Recycling [online] – Neuer Standard für die Klassifizierung von Kunststoff-Rezyklaten veröffentlicht. DIN e. V. [retrieved on: 26.10.2022], available at: https://www.din.de/de/din-und-seine-partner/presse/mitteilungen/schub-fuers-kunststoff-recycling-827024

Doose, S.; Mayer, J. K.; Michalowski, P. und Kwade, A. (2021): Challenges in Ecofriendly Battery Recycling and Closed Material Cycles: A Perspective on Future Lithium Battery Generations. In: Metals, 11 (2), S. 291. Metals [retrieved on: 28.10.2022]. doi:10.3390/met11020291

Dornbusch, H.-J.; Hannes, L.; Santjer, M.; Böhm, C.; Wüst, S.; Zwisele, B.; Kern, M.; Siepenkothen, H.-J. und Kanthak, M. (2020): Vergleichende Analyse von Siedlungsrestabfällen aus repräsentativen Regionen in Deutschland zur Bestimmung des Anteils an Problemstoffen und verwertbaren Materialien. Umweltbundesamt, Dessau-Roßlau [retrieved on: 27.10.2022], available at: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/texte_113-2020_analyse_von_siedlungsrestabfaellen_abschlussbericht.pdf

Duesenfeld GmbH (2022): Lizenzierung der Duesenfeld Patente [online]. Duesenfeld GmbH [retrieved on: 28.10.2022], available at: https://www.duesenfeld.com/lizenzierung.html

Dürfeld, K. (2021): Lithium-Dendriten auf der Spur: Wie zerstörerische Strukturen in Batterien wachsen [online]. Helmholtz-Zentrum Berlin für Materialien und Energie [retrieved on: 27.10.2022], available at: https://www.helmholtz-berlin.de/pubbin/news_seite?nid=23163&sprache=de&seitenid=74699

Ecologic Institut gemeinnützige GmbH (2022): Tracer Based Sorting | Plastik in der Umwelt [online]. Ecologic Institut gemeinnützige GmbH [retrieved on: 26.10.2022], available at: https://bmbf-plastik.de/de/taxonomy/term/162

energie-experten.org (2022): PERC-Solarzelle: Rückseitenpassivierung, Effizienz und Degradation [online]. Greenhouse Media GmbH [retrieved on: 08.12.2022], available at: https://www.energie-experten.org/erneuerbare-energien/solarenergie/solarzelle/perc

Erneuerbar mobil (2022): EcoBatRec [online] – Demonstrationsanlage für ein kostenneutrales, ressourceneffizientes Processing ausgedienter Li-Ion Batterien der Elektromobilität. Bundesministerium für Wirtschaft und Klimaschutz, 24.10.2022 [retrieved on: 28.10.2022], available at: https://www.erneuerbar-mobil.de/projekte/ecobatrec

EU-Recycling Magazin (2022a): Photovoltaikanlagen: Das Recycling entwickelt sich. In: EU-Recycling Magazin, S. 32 [retrieved on: 28.10.2022], available at: https://eu-recycling.com/Archive/34578

EU-Recycling Magazin (2022b): Polysecure und Zeiss entwickeln neue Sortiertechnologie. In: EU-Recycling Magazin [retrieved on: 26.10.2022], available at: https://eu-recycling.com/Archive/34178?msclkid=fc20e8f7d12a11ecadb6b5575b4a7bbb

EuRIC (2022): Evaluating EU rules on waste from electrical and electronic equipment (WEEE) – Feedback from the European recycling industry [retrieved on: 29.03.2023], available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13420-Elektro-und-Elektronik-Altgerate-Bewertung-der-EU-Vorschriften/F3353376_de

Europäische Kommission (2020): Vorschlag für eine Verordnung des europäischen Parlaments und des Rates über Batterien und Altbatterien, zur Aufhebung der Richtlinie 2006/66/EG und zur Änderung der Verordnung (EU) 2019/1020 [retrieved on: 31.10.2022], available at: https://eur-lex.europa.eu/legal-content/DE/TXT/HTML/?uri=CELEX:52020PC0798&from=EN

Europäische Kommission (2022): Europäische Batterie-Allianz. Europäische Kommission, Brüssel [retrieved on: 27.10.2022], available at: https://ec.europa.eu/commission/presscorner/detail/de/IP_22_1256

Europäisches Parlament (2022): Circular economy: definition, importance and benefits [online], available at: https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

European Commission (2023): F3353337 European WEEE Registers Network (EWRN) [online], 16.02.2023 [retrieved on: 20.02.2023], available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13420-Elektro-und-Elektronik-Altgerate-Bewertung-der-EU-Vorschriften/F3353337_de

European Recycling Platform (2022): Comments on the evaluation of EU rules on waste electrical and electronic equipment. European Recycling Platform, Paris/Mainz [retrieved on: 08.12.2022], available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13420-Elektro-und-Elektronik-Altgerate-Bewertung-der-EU-Vorschriften/F3353387_de

Evonik Industries AG (2021): Evonik ist Teil des EU-Verbundprojekts ReProSolar zum vollständigen Recycling von Photovoltaik-Modulen - Evonik Industries [online]. Evonik Industries AG, 15.06.2021 [retrieved on: 02.12.2022], available at: https://corporate.evonik.com/de/evonik-ist-teil-des-eu-verbundprojekts-reprosolar-zum-vollstaendigen-recycling-von-photovoltaik-modu-159496.html

EWRN (2022): Call for Evidence for an Evaluation – Waste electrical and electronic equipment - Evaluating the EU rules. european weee registers network, Nürnberg [retrieved on: 08.12.2022], available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13420-Elektro-und-Elektronik-Altgerate-Bewertung-der-EU-Vorschriften/F3353337_de

FLAXRES GmbH (2022): Technologie [online]. FLAXRES GmbH [retrieved on: 02.12.2022], available at: https://www.flaxres.com/de/technologie/

Fluchs, S. (2021): Batterierecycling: Potenziale zur Reduzierung der Rohstoffabhängigkeit – IW-Kurzbericht 35/2021. Institut der deutschen Wirtschaft, Köln [retrieved on: 27.10.2022], available at: https://www.iwkoeln.de/studien/sarah-fluchs-potenziale-zur-reduzierung-der-rohstoffabhaengigkeit-511335.html

Folayan, T.-O.; Lipson, A. L.; Durham, J. L.; Pinegar, H.; Liu, D. und Pan, L. (2021): Direct Recycling of Blended Cathode Materials by Froth Flotation. In: Energy Technology, 9 (10), S. 2100468. ISSN 2194-4288 [retrieved on: 31.10.2022]. doi:10.1002/ente.202100468

Forum Rezyklat (2022): Für Unternehmen [online]. GS1 Germany GmbH [retrieved on: 26.10.2022], available at: https://www.forum-rezyklat.de/fuer-unternehmen/

Fraunhofer IBP (2012): Life Cycle Assessment (LCA) screening of the Maltha recycling process for Si-PV modules. Fraunhofer IBP - Department Life Cycle Engineering, Stuttgart [retrieved on: 28.10.2022], available at: www.pvcycle.org.uk/wp-content/uploads/Exec-Summary-LCA-Screening-of-a-Recycling-process-of-silicon-based-PV-modules-2012-07.pdf

Fraunhofer UMSICHT (2022): Recycling von Elektronik, Elektronikschrott und Elektrogeräten [online]. Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT, Institutsteil Sulzbach-Rosenberg [retrieved on: 31.10.2022], available at: https://www.umsicht-suro.fraunhofer.de/de/unsere-loesungen/icycle-technologie-plattform.html

Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit LBF (2021): Upcycling: Neue Werkstoffe aus PET-Abfällen des gelben Sacks [online]. Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit LBF [retrieved on: 31.10.2022], available at: https://www.lbf.fraunhofer.de/de/presse/presseinformationen/upcycling.html

Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA (2022): Industrielle Demontage von Batteriemodulen und E-Motoren DeMoBat [online]. Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA [retrieved on: 28.10.2022], available at: https://www.ipa.fraunhofer.de/de/referenzprojekte/DeMoBat.html

Fraunhofer-Institut für Solare Energiesysteme ISE (2022): PERC-Solarzellen aus 100 Prozent recyceltem Silizium [online]. Fraunhofer-Institut für Solare Energiesysteme ISE [retrieved on: 02.12.2022], available at: https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/2022/perc-solarzellen-aus-recyceltem-silizium-hergestellt.html

Fraunhofer-Institut für Verfahrenstechnik und Verpackung IVV (2022): Kreislaufwirtschaft für phthalathaltige PVC-Fußböden [online]. Fraunhofer-Institut für Verfahrenstechnik und Verpackung IVV [retrieved on: 31.10.2022], available at: https://www.ivv.fraunhofer.de/de/recycling-umwelt/recycling-von-kontaminierten-kunststoffen/circular-flooring.html

Fraunhofer-Institut für Verfahrenstechnik und Verpackung IVV (2023): Nachhaltige Kreislaufwirtschaft durch Künstliche Intelligenz bei Kunststoffabfällen [online], 21.02.2023 [retrieved on: 21.02.2023], available at: https://www.ivv.fraunhofer.de/de/presseinformationen/bmbf-foerdermasssnahme-ki-anwendungshub-kunststoffverpackungen.html

Gao, H.; Yan, Q.; Xu, P.; Liu, H.; Li, M.; Liu, P.; Luo, J. und Chen, Z. (2020): Efficient Direct Recycling of Degraded LiMn2O4 Cathodes by One-Step Hydrothermal Relithiation. In: ACS applied materials & interfaces, 12 (46), S. 51546–51554. ACS applied materials & interfaces [retrieved on: 31.10.2022]. doi:10.1021/acsami.0c15704

Gosten, A. (2022): Ist das Kreislaufwirtschaftsgesetz Teil des Problems oder Teil der Lösung auf dem Weg in die Kreislaufwirtschaft? Berliner Abfallwirtschafts- und Energie-Konferenz. TK Verlag GmbH, Berlin [retrieved on: 08.12.2022], available at: https://www.dgaw.de/fileadmin/data/download/pdf/220516_BAEK_KrWG_Go_TK_final.pdf

greenBatt (2021a): DIGISORT - Digitalisierung mechanischer Sortierprozesse [online]. Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 28.04.2021 [retrieved on: 31.10.2022], available at: https://www.greenbatt-cluster.de/de/projekte/digisort/

greenBatt (2021b): EarLiMet – Early Stage-Metallrückgewinnung für das energie- und ressourceneffiziente Recycling von Li-Ionen-Batterien [online]. Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 14.07.2021 [retrieved on: 31.10.2022], available at: https://www.greenbatt-cluster.de/de/projekte/earlimet/

greenBatt (2021c): EVanBatter - Entwicklung einer gegenüber Verunreinigungen robusten Resyntheseroute von Aktivmaterialien für Lithium-Ionen-Batterien [online]. Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 14.07.2021 [retrieved on: 31.10.2022], available at: https://www.greenbatt-cluster.de/de/projekte/evanbatter/

greenBatt (2021d): Kompetenzcluster Recycling & Grüne Batterie [online]. Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 22.07.2021 [retrieved on: 28.10.2022], available at: https://www.greenbatt-cluster.de/de/

greenBatt (2021e): LOWVOLMON - Monitoring schwerflüchtiger Elektrolyte in der mechanischen Recyclingprozesskette [online]. Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 14.07.2021 [retrieved on: 31.10.2022], available at: https://www.greenbatt-cluster.de/de/projekte/lowvolmon/

greenBatt (2021f): Projekte [online]. Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 20.09.2021 [retrieved on: 28.10.2022], available at: https://www.greenbatt-cluster.de/de/projekte/

greenBatt (2021g): PyroLith – Entwicklung eines stabilen Prozesses auf Basis der Prozessketten Pyrometallurgie-Schlackenaufbereitung-Hydrometallurgie zur Rückgewinnung von Li aus Mn-haltigen Schlacken [online]. Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 14.07.2021 [retrieved on: 31.10.2022], available at: https://www.greenbatt-cluster.de/de/projekte/pyrolith/

greenBatt (2023): DemoSens - Digitalisierung mechanische Aufbereitung [online], 14.07.2021 [retrieved on: 28.03.2023], available at: https://www.greenbatt-cluster.de/de/projekte/demosens/

GS1 Germany GmbH (2022): GS1 Standards im Überblick [online]. GS1 Germany GmbH [retrieved on: 31.10.2022], available at: https://www.gs1-germany.de/gs1-standards/

Hagelüken, C. (2022): Recycling von (Edel)metallen aus Elektroaltgeräten [online]. In: Porth, M. und Schüttrump, H., Hg. Wasser, Energie und Umwelt, Springer Fachmedien Wiesbaden, Wiesbaden, S. 101–111. ISBN 9783658356071 [retrieved on: 08.12.2022], available at: https://www.springerprofessional.de/recycling-von-edel-metallen-aus-elektroaltgeraeten/20122876

Halleux, V. (2022): New EU regulatory framework for batteries – Setting sustainability requirements. EPRS - European Parliamentary Research Service [retrieved on: 26.10.2022], available at: https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)689337

hamos GmbH (2023): Elektrostatischer Separator für saubere Kunststoffe [online], 17.03.2023 [retrieved on: 17.03.2023], available at: https://www.hamos.com/produkte/elektrostatische-kunststoff-kunststoff-separatoren-hamos-eks

Helmholtz-Zentrum Dresden - Rossendorf e. V. (2021): Wenn Batterien zu Schaum werden [online] – HZDR-Doktorandin mit Konzept zum verbesserten Batterie-Recycling beim Falling Walls Wettbewerb. Helmholtz-Zentrum Dresden - Rossendorf e. V. [retrieved on: 31.10.2022], available at: https://www.hzdr.de/db/Cms?pOid=64639&pNid=0

Hofmann, A. (2017): LAGA Bericht 31a – Umsetzung des Elektro- und Elektronikgerätegesetzes. Anforderungen an die Entsorgung von Elektro- und Elektronikaltgeräten. Bund/Länder-Arbeitsgemeinschaft Abfall, München [retrieved on: 21.10.2022], available at: https://www.laga-online.de/documents/m-31-a_1517834714.pdf

Hofmann, A. (2018): Mitteilung der Bund/Länder-Arbeitsgemeinschaft Abfall (LAGA) 31 B. Bund/Länder-Arbeitsgemeinschaft Abfall, München [retrieved on: 28.10.2022], available at: https://www.laga-online.de/documents/m-31b-18-04-2018-neu_1527151713.pdf

impulstec (2022): HighTech Recycling [online]. ImpulsTec GmbH [retrieved on: 08.12.2022], available at: https://impulstec.com/#elektronikschrottrecycling

IRENA und IEA-PVPS (2016): End-of-Life Management: Solar Photovoltaic Panels. International Renewable Energy Agency und International Energy Agency Photovoltaic Power Systems.

Janz, A.; Prelle, R.; Müller, F. und Bilitewski, B. (2009): Grenzüberschreitende Ströme von Elektroaltgeräten. In: Müll und Abfall, (3), S. 126–132. Müll und Abfall. doi:10.37307/j.1863-9763.2009.03.07

Jongebloed, K. und Kessens, L. (2021): Mehrheit der Deutschen für ein Pfand auf Smartphones [online]. Deutsche Bundesstiftung Umwelt [retrieved on: 27.10.2022], available at: https://www.dbu.de/123artikel39077_2442.html

Juschkat, K. (2021): Warum Lithium-Ionen-Akkus explodieren können. In: elektrotechnik Automatisierung [retrieved on: 27.10.2022], available at: https://www.elektrotechnik.vogel.de/warum-lithium-ionen-akkus-explodieren-koennen-a-1002438/

Kempkens, W. (2021): Deutschland produziert Lithium bald selbst. In: BWK Energie [retrieved on: 27.10.2022], available at: https://www.ingenieur.de/fachmedien/bwk/energiespeicher/deutschland-produziert-lithium-bald-selbst/

Knappe, F.; Reinhardt, J.; Kauertz, B.; Oetjen-Dehne, R.; Buschow, N.; Ritthoff, M.; Wilts, H. und Lehmann, M. (2021): Technische Potenzialanalyse zur Steigerung des Kunststoffrecyclings und des Rezyklateinsatzes. Umweltbundesamt, Dessau-Roßlau [retrieved on: 26.10.2022], available at: https://www.umweltbundesamt.de/publikationen/technische-potenzialanalyse-zur-steigerung-des

Köhnlechner, R.; Jung, H. und Geisler, W. (2012): Kunststoffrecycling – Elektrostatische Trennung separiert auch schwarze Kunststoffe [online]. In: Process [retrieved on: 17.03.2023], available at: https://www.process.vogel.de/kunststoffrecycling-elektrostatische-trennung-separiert-auch-schwarze-kunststoffe-a-386970/?p=2

Kompetenznetzwerk Lithium-Ionen-Batterien e. V. (2018): Batterie 2020 - Förderung [online]. Kompetenznetzwerk Lithium-Ionen-Batterien e. V. [retrieved on: 28.10.2022], available at: https://batterie-2020.de/foerderung/?x=165?x=166

Krüger, F. (2020): ATA - Ad-hoc-Ausschuss Kennzeichnung / Identifizierung von Kunststoffen. Bund-Länder-Arbeitsgemeinschaft Abfall, Berlin [retrieved on: 09.11.2022], available at: https://www.laga-online.de/documents/kik_bericht_18_1591617236.-v_06022020f

KUKA Deutschland GmbH (2022): Recycling-Roboter im Einsatz gegen Elektroschrott [online]. KUKA Deutschland GmbH, 05.04.2022 [retrieved on: 02.12.2022], available at: https://www.kuka.com/de-de/branchen/loesungsdatenbank/2022/04/votechnik-roboter-recycelt-elektroschrott

Kummer, S.; Strobelt, A.; Kohlmeyer, R.; Kitazume, C.; Oehme, I. und Schnepel, C. (2020): Empfehlungen des UBA für die Weiterentwicklung der Behandlungsanforderungen nach ElektroG. Umweltbundesamt, Dessau-Roßlau [retrieved on: 28.10.2022], available at: https://www.umweltbundesamt.de/publikationen/empfehlungen-des-uba-fuer-die-weiterentwicklung-der

Kunz Rechtsanwälte (2021): Neue gesetzliche Regelungen für Kunststoffprodukte und –abfälle [online]. Kunz Rechtsanwälte [retrieved on: 26.10.2022], available at: https://www.kunzrechtsanwaelte.de/aktuelles/news/neue-gesetzliche-regelungen-fuer-kunststoffprodukte-und-abfaelle

Land Nordrhein-Westfalen (2022): Batterie-Recycling in Ibbenbüren nimmt Fahrt auf: Wirtschafts- und Innovationsminister Prof. Pinkwart überreicht Letter of Intent [online]. Land Nordrhein-Westfalen [retrieved on: 28.10.2022], available at: https://www.land.nrw/pressemitteilung/batterie-recycling-ibbenbueren-nimmt-fahrt-auf-wirtschafts-und-innovationsminister

Land.NRW (2021): Wettbewerb „InnovationUmweltwirtschaft.NRW“: 34 Projekte ausgewählt | Land.NRW [online], 29.03.2023 [retrieved on: 29.03.2023], available at: https://www.land.nrw/pressemitteilung/wettbewerb-innovationumweltwirtschaftnrw-34-projekte-ausgewaehlt

Lange, U. (2022): VDI ZRE Fachgespräch "Circular Economy und ressourceneffiziente Kreislaufwirtschaft" – Der Weg ins zirkuläre Wirtschaften. VDI Zentrum Ressourceneffizienz GmbH, Berlin [retrieved on: 10.02.2023], available at: https://www.ressource-deutschland.de/service/publikationen/detailseite/fachgespraech-circular-economy/

Lange, U. (2021): Wahre Kreislaufwirtschaft. In: Der Mittelstand, (6-2021), S. 66 [retrieved on: 03.11.2022], available at: https://www.bvmw.de/fileadmin/01-Presse_und_News/Publikationen/DER_Mittelstand/2021/06-2021/6-21_DER_Mittelstand_web.pdf

Lindner, C.; Schmitt, J. und Hein, J. (2020): Stoffstrombild Kunststoffe in Deutschland 2019 – Kurzfassung der Conversio Studie. Conversio Market & Strategy GmbH, Mainaschaff [retrieved on: 03.11.2022], available at: https://www.conversio-gmbh.com/res/News_Media/2020/Kurzfassung_Stoffstrombild_2019.pdf

Lindner, C.; Schmitt, J.; Fischer, E. und Hein, J. (2022): Stoffstrombild Kunststoffe in Deutschland 2021: Zahlen und Fakten zum Lebensweg von Kunststoffen – Kurzfassung der Conversio Studie. Conversio Market & Strategy GmbH [retrieved on: 19.12.2022], available at: https://www.bvse.de/dateien2020/2-PDF/01-Nachrichten/03-Kunststoff/2022/Kurzfassung_Stoffstrombild_2021_13102022_1_.pdf

LionCare GmbH (2022): Defekt, Brand oder Explosion - Folgen von beschädigten Lithium-Batterien und Akkus [online]. LionCare GmbH [retrieved on: 27.10.2022], available at: https://www.lion-care.com/defekt-brand-und-explosion-von-lithium-ionen-akkus

Löhle, S.; Schmiedel, U. und Bartnik, S. (2020): Analyse der Datenerhebungen nach ElektroG und UStatG über das Berichtsjahr 2018 zur Vorbereitung der EU-Berichtspflichten 2020. Umweltbundesamt, Dessau-Roßlau [retrieved on: 28.10.2022], available at: https://www.umweltbundesamt.de/publikationen/analyse-datenerhebungen-elektrog-ustatg-2018

Löhle, S.; Schmiedel, U.; Bartnik, S. und Oehme, I. (2019): Analyse der Datenerhebungen nach ElektroG und UStatG über das Berichtsjahr 2017 zur Vorbereitung der EU-Berichtspflichten 2019. Umweltbundesamt, Dessau-Roßlau [retrieved on: 28.10.2022], available at: https://www.umweltbundesamt.de/publikationen/analyse-der-datenerhebungen-nach-elektrog-ustatg-1

Martens, H. und Goldmann, D. (2016): Recycling von Elektro- und Elektronikgeräten. In: Martens, H. und Goldmann, D., Hg. Recyclingtechnik, Springer Fachmedien Wiesbaden, Wiesbaden, S. 439–475. ISBN 978-3-658-02785-8.

Marwede, M. (2013): Cycling critical absorber materials of CdTe- and CIGS-photovoltaics – Material efficiency along the life-cycle. Universität Augsburg, Augsburg [retrieved on: 31.10.2022], available at: d-nb.info/1077703074/34

MEILO Gesellschaft zur Rückgewinnung sortierter Werkstoffe mbH & Co. KG (2022): Hochwertiger Output [online]. MEILO Gesellschaft zur Rückgewinnung sortierter Werkstoffe mbH & Co. KG [retrieved on: 26.10.2022], available at: https://www.meilo-gernsheim.de/leistungen/hochwertiger-output

Meyer, K. (2022): Neue Bundesregierung muss Recht auf Reparatur wirksam umsetzen: Der Teufel liegt im Detail [online]. Runder Tisch Reparatur e.V. [retrieved on: 08.12.2022], available at: https://runder-tisch-reparatur.de/neue-bundesregierung-muss-recht-auf-reparatur-wirksam-umsetzen-der-teufel-liegt-im-detail/

Ministerium für Klimaschutz, Umwelt, Energie und Mobilität des Landes Rheinland-Pfalz (2022): Eder: „Ein Quantensprung beim Kunststoffrecycling" [online]. Ministerium für Klimaschutz, Umwelt, Energie und Mobilität des Landes Rheinland-Pfalz [retrieved on: 26.10.2022], available at: https://mkuem.rlp.de/de/pressemeldungen/detail/news/News/detail/eder-ein-quantensprung-beim-kunststoffrecycling/?no_cache=1&cHash=72835fe61f468f9cf982c6c7214300ff

Monneron-Enaud, B. und Kramer, J. (2021): Bakterien helfen beim Recycling von Elektroschrott. In: BIOspektrum, 27 (2), S. 214. ISSN 0947-0867 [retrieved on: 02.12.2022]. doi:10.1007/s12268-021-1551-2

Neef, C.; Schmaltz, T. und Thielmann, A. (2021): Recycling von Lithium-Ionen-Batterien: Chancen und Heraus forderungen für den Maschinen- und Anlagenbau – Kurzstudie im Auftrag der IMPULS-Stiftung. Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe [retrieved on: 03.11.2022], available at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2021/VDMA_Kurzstudie_Batterierecycling.pdf

Newsroom Kunststoffverpackungen (2021): BASF und Cyclos-HTP untersuchen mechanische Recyclingfähigkeit von PA/PE-Verbundfolien [online]. IK Industrievereinigung Kunststoffverpackungen e.V., 09.10.2021 [retrieved on: 04.11.2022], available at: https://newsroom.kunststoffverpackungen.de/2021/07/07/recyclingfaehigkeit-von-pa-pe-verbundfolien/

packaging journal (2020): Neues Schwarz ermöglicht das Recycling dunkler Kunststoffe. In: packaging journal [retrieved on: 26.10.2022], available at: https://packaging-journal.de/neues-schwarz-ermoeglicht-das-recycling-dunkler-kunststoffe/

Paschetag, M.; Scholl, S. und Eichert, C. (2022): Wie lösen wir das Recyclingproblem der Mehrschichtfolie? In: plastverarbeiter [retrieved on: 26.10.2022], available at: https://www.plastverarbeiter.de/verarbeitungs-verfahren/kunststoffrecycling/rezyklatherstellung-aus-multilayer-folien-und-tiefziehschalen-558.html

Plastverarbeiter (2021): Flaschen aus enzymatisch recyceltem PET vorgestellt. In: plastverarbeiter [retrieved on: 26.10.2022], available at: https://www.plastverarbeiter.de/verarbeitungsverfahren/flaschen-aus-enzymatisch-recyceltem-pet-vorgestellt.html

Pohl, R. und Heitmann, B. (2019): Aufarbeitung von Altmodulen und Rückführung von Wertstoffen in den Stoffkreislauf (EoL-Cycle) : Abschlussbericht. Reiling Glas Recycling GmbH & Co. KG, Marienfeld [retrieved on: 31.10.2022], available at: https://www.tib.eu/de/suchen?tx_tibsearch_search%5Baction%5D=download&tx_tibsearch_search%5Bcontroller%5D=Download&tx_tibsearch_search%5Bdocid%5D=TIBKAT%3A1738022528&cHash=f02ec6ed714c40d72d0e55142f0dc764#download-mark

Polysecure GmbH (2022): Verlässlich Sortieren [online]. Polysecure GmbH [retrieved on: 26.10.2022], available at: https://www.polysecure.eu/verlaesslich-sortieren

R-Cycle (2022a): Mit dem offenen digitalen Standard R-Cycle Kunststoffe recyclen [online]. ProData GmbH [retrieved on: 26.10.2022], available at: https://www.r-cycle.org/

R-Cycle (2022b): Pilotprojekt: Digitale Produktpässe für smarte Digital-Watermark-Blasform-Verpackungen [online]. ProData GmbH [retrieved on: 26.10.2022], available at: https://www.r-cycle.org/intelligente-blasform-verpackung-identifizierbare-digitales-wasserzeichen-flasche-kanister/

Redux GmbH (2022): Nachhaltiges Recycling von Lithium-Ionen-Akkus [online]. Redux GmbH, 04.02.2022 [retrieved on: 28.10.2022], available at: https://www.redux-recycling.com/de/services/lithium-ionenbatterien/

Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen (2021): Demonstrationszentrum Batterie-Recycling [online]. Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, 08.12.2021 [retrieved on: 28.10.2022], available at: https://www.controlling.rwth-aachen.de/cms/Controlling/Forschung/Forschungsprojekte/Abgeschlossene-Projekte/~mnwev/Demonstrationszentrum-Batterie-Recycling/

RINOVASOL (2022): Technologie zum Modulrecycling [online] – Kurze Wege - große Wirkung. Rinovasol Global Services B. V. [retrieved on: 02.12.2022], available at: https://www.rinovasol.de/modul-re-using/technologie

RITTEC Umwelttechnik GmbH (2022): revolPET® Ein Kreislauf für Kunststoff [online]. RITTEC Umwelttechnik GmbH [retrieved on: 26.10.2022], available at: https://www.rittec.eu/loesungen/revolpet.html

Ritthoff, M.; Müller, A.; Hopfensack, L.; Brüning, R.; Wolf, J. und Piehl, F. (2022): Methoden und Normen zur Bewertung der Reparierbarkeit von Elektro- und Elektronikgeräten – Stärkung der Materialeffizienz unter der Ökodesign- Richtlinie. Umweltbundesamt, Dessau-Roßlau [retrieved on: 08.12.2022], available at: https://www.umweltbundesamt.de/publikationen/methoden-normen-zur-bewertung-der-reparierbarkeit

ROSI SAS (2022): Recycling von Photovoltaik-Modulen [online]. ROSI SAS [retrieved on: 02.12.2022], available at: https://www.rosi-solar.com/de/recycling-von-photovoltaik-modulen/

Sander, K. und Schilling, S. (2010): Optimierung der Steuerung und Kontrolle grenzüberschreitender Stoffströme bei Elektroaltgeräten / Elektroschrott. Umweltbundesamt, Dessau-Roßlau [retrieved on: 08.12.2022], available at: https://www.umweltbundesamt.de/publikationen/optimierung-steuerung-kontrolle

Sander, K.; Otto, S. J.; Rödig, L. und Wagner, L. (2018): Behandlung von Elektroaltgeräten (EAG) unter Ressourcen- und Schadstoffaspekten – Abschlussbericht. Umweltbundesamt, Dessau-Roßlau [retrieved on: 02.12.2022], available at: https://www.umweltbundesamt.de/publikationen/behandlung-von-elektroaltgeraeten-eag-unter

Saubermacher (2022): Zweites Leben: Alte E-Autobatterien sinnvoll nutzbar [online]. Saubermacher Dienstleistungs AG, 05.07.2022 [retrieved on: 28.10.2022], available at: https://saubermacher.at/presse/stationaerer-speicher-aus-alten-e-autobatterien/

Sauer, F.; Choi, B.-K.; Beck, G. und Wickleder, M. (2019): Recovery of Tantalum from Printed Circuit Boards – An Overview of the IRETA Project. In: World of Metallurgy - Erzmetall, (72), S. 216–222 [retrieved on: 02.12.2022], available at: https://www.researchgate.net/publication/334882118_Recovery_of_Tantalum_from_Printed_Circuit_Boards_-_An_Overview_of_the_IRETA_Project

Schick, B. (2022): Neu entdecktes Enzym zersetzt PET in Rekordzeit. In: Kunststoff Magazin [retrieved on: 26.10.2022], available at: https://www.kunststoff-magazin.de/zerkleinerung-recycling/neu-entdecktes-enzym-zersetzt-pet-in-rekordzeit.htm

Schiller, C.; Amrhein, U.; Ehrlinspiel, M.; Jacob, A. M.; Endres, H.-J. und Wilts, H. (2020): Wertsachen. Warum der Markt für recycelten Kunststoff nicht funktioniert ...und wie sich das ändern könnte. Röchling Stiftung GmbH, Mannheim, Polyproblem Report [retrieved on: 20.10.2022], available at: https://polyproblem.org/2021/report-wertsachen/

Sojka, R.; Pan, Q. und Billmann, L. (2020): Comparative study of Li-ion battery recycling processes. ACCUREC Recycling GmbH, Krefeld [retrieved on: 28.10.2022], available at: https://accurec.de/wp-content/uploads/2021/04/Accurec-Comparative-study.pdf

Statistisches Bundesamt (2021): Export von Plastikmüll 2020: 33 % weniger Kunststoffabfälle ausgeführt als vor zehn Jahren [online]. Statistisches Bundesamt, 05.04.2022 [retrieved on: 24.10.2022], available at: https://www.destatis.de/DE/Presse/Pressemitteilungen/2021/03/PD21_N016_51.html

Statistisches Bundesamt (2022a):2021 wurde 25 % weniger Plastikmüll exportiert als im Vorjahr, Wiesbaden [retrieved on: 19.12.2022], available at: https://www.destatis.de/DE/Presse/Pressemitteilungen/2022/06/PD22_N035_51.html

Statistisches Bundesamt (2022b): Zur Erstbehandlung angenommene Elektro- und Elektronikaltgeräte [online]. Statistisches Bundesamt, 11.02.2022 [retrieved on: 28.10.2022], available at: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Abfallwirtschaft/Tabellen/liste-erstbehandlung.html;jsessionid=2696AD8D4EEF20F9E98D209A5AAE49ED.live741#fussnote-1-588264

Stiftung GRS Batterien (2020): Altbatterien sicher verpacken, lagern und transportieren – Der GRS-Sicherheitsstandard. Stiftung GRS Batterien, Hamburg [retrieved on: 27.10.2022], available at: https://www.grs-batterien.de/fileadmin/Downloads/Sicherheit/GRS-Merkblatt_Sicherheitsstandard_V01_Feb2021.pdf

Stiftung GRS Batterien (2022): Verpackung [online]. Stiftung Gemeinsames Rücknahmesystem Batterien [retrieved on: 27.10.2022], available at: https://www.grs-batterien.de/sicherheit/sicherheitsforum/verpackung/#c2558

Strutzberg, L.; Lange, U. und Frerichs, T. (2022): Rohstoffkritikalität und Kreislaufwirtschaft – Die Grenzen des Wachstums nutzen. In: Zeitschrift für wirtschaftlichen Fabrikbetrieb, 117 (7-8), S. 489–492. Zeitschrift für wirtschaftlichen Fabrikbetrieb [retrieved on: 31.10.2022]. doi:10.1515/zwf-2022-1099

Tao, J. und Yu, S. (2015): Review on feasible recycling pathways and technologies of solar photovoltaic modules. In: Solar Energy Materials and Solar Cells, 141, S. 108–124. ISSN 09270248. doi:10.1016/j.solmat.2015.05.005

Technische Hochschule Aschaffenburg (2022): IRVE e-Waste Recycling [online]. Technische Hochschule Aschaffenburg [retrieved on: 02.12.2022], available at: https://www.th-ab.de/transfer/projekte/irve-e-waste-recycling

The Battery Pass (15.11.2022): Battery Pass [online], 15.11.2022 [retrieved on: 21.02.2023], available at: https://thebatterypass.eu/

Thews, M. (2022): Start eines Recyclinglabels bereits in diesem Haushalt [online]. Michael Thews [retrieved on: 02.11.2022], available at: https://www.michaelthews.de/2022/05/13/start-eines-recyclinglabels-bereits-in-diesem-haushalt/

U.S. Geological Survey (2020): Mineral commodity summaries 2020. U.S. Geological Survey, Reston [retrieved on: 27.10.2022], available at: https://pubs.er.usgs.gov/publication/mcs2020

Umicore Precious Metals Refining (2022): Recyclables - E-scrap [online]. Umicore Precious Metals Refining [retrieved on: 02.12.2022], available at: https://pmr.umicore.com/en/recyclables/e-scrap#tabs

Umwelt- und Energie Report (2022): Recyclingmaterialien: ...eine „richtungsweisende Entscheidung für weitere Stoffströme!" ? In: Umwelt- und Energie Report [retrieved on: 27.10.2022], available at: https://www.umwelt-energie-report.de/2022/03/recyclingmaterialien-eine-richtungsweisende-entscheidung-fuer-weitere-stoffstroeme.html

Umweltbundesamt (2021): Altbatterien [online]. Umweltbundesamt [retrieved on: 31.10.2022], available at: https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/altbatterien#im-jahr-2020-hat-deutschland-alle-von-der-eu-geforderten-mindestziele-erreicht

Umweltbundesamt (2022a): „E-Waste Day“ ruft zur korrekten Entsorgung von Elektrogeräten auf [online]. Umweltbundesamt [retrieved on: 08.12.2022], available at: https://www.umweltbundesamt.de/presse/pressemitteilungen/e-waste-day-ruft-zur-korrekten-entsorgung-von

Umweltbundesamt (2022b): Altauto, Altautoverwertung [online]. Umweltbundesamt [retrieved on: 27.10.2022], available at: https://www.umweltbundesamt.de/umwelttipps-fuer-den-alltag/mobilitaet/altauto-altautoverwertung#hintergrund

Umweltbundesamt (2022c): Elektro- und Elektronikaltgeräte [online]. Umweltbundesamt [retrieved on: 28.10.2022], available at: https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/elektro-elektronikaltgeraete

Umweltbundesamt (2022d): Elektroaltgeräte [online]. Umweltbundesamt [retrieved on: 02.12.2022], available at: https://www.umweltbundesamt.de/themen/abfall-ressourcen/produktverantwortung-in-der-abfallwirtschaft/elektroaltgeraete#elektronikaltgerate-in-deutschland

Vallero, C. (2022): Hightech Recycling [online] – KfW Award Gründen. KfW [retrieved on: 02.12.2022], available at: https://www.kfw.de/stories/wirtschaft/gruenden/luxchemtech/

VDI 2343 Blatt 4:2012-01: Verein Deutscher Ingenieure e.V., Recycling elektrischer und elektronischer Geräte - Aufbereitung, Beuth Verlag GmbH, Berlin.

VDI 4800 Blatt 2:2018-03: Verein Deutscher Ingenieure e.V., Ressourceneffizienz – Bewertung des Rohstoffaufwandes, Beuth Verlag GmbH, Berlin.

VDI e. V. (2022): Circular Economy für Kunststoffe neu denken (White Paper), Verein Deutscher Ingenieure e.V.

VDI Zentrum Ressourceneffizienz GmbH (2018): Kunststoffrecycling–Ressourceneffizienz durch optimierte Sortierverfahren. YouTube [retrieved on: 03.11.2022], available at: https://www.youtube.com/watch?v=I_fUpP-hq3A

VERE e.V. (2022): Stellungnahme zur Initiative „Elektro- und Elektronik-Altgeräte – Bewertung der EU-Vorschriften“. Verband zur Rücknahme und Verwertung von Elektro- und Elektronik-Altgeräten e. V., Hamburg [retrieved on: 08.12.2022], available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13420-Elektro-und-Elektronik-Altgerate-Bewertung-der-EU-Vorschriften/F3353403_de

Wirth, H. (2022): Aktuelle Fakten zur Photovoltaik in Deutschland. Fraunhofer ISE [retrieved on: 20.02.2023], available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/aktuelle-fakten-zur-photovoltaik-in-deutschland.pdf

Wolf, J.; Brüning, R.; Nellesen, L. und Schiemann, J. (2017): Anforderungen an die Behandlung spezifischer Elektroaltgeräte unter Ressourcen- und Schadstoffaspekten. Umweltbundesamt, Dessau-Roßlau [retrieved on: 31.10.2022], available at: https://www.umweltbundesamt.de/publikationen/anforderungen-an-die-behandlung-spezifischer

ZVEI - Zentralverband Elektrotechnik- und Elektronikindustrie e. V. (2021): Faktenblatt zu Recycling von Batterien. ZVEI - Zentralverband Elektrotechnik- und Elektronikindustrie e. V., Frankfurt am Main [retrieved on: 31.10.2022], available at: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Pressebereich/2021-051_Batteriemarkt_waechst_waehrend_der_Pandemie_stark/ZVEI_Faktenblatt_Recycling.pdf

VDI Zentrum Ressourceneffizienz
Bülowstraße 78
10783 Berlin
Tel. +49 30-2759506-0
zre-info@vdi.de
www.resource-germany.com