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Ecological and Economic Assessment of Resource Use

Use of recycled plastics in packaging materials

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Study: Ecological and Economic Assessment of the Use of Resources –
Use of recycled plastics in packaging materials

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LIST OF ABBREVIATIONS

AI	Artificial intelligence
APOS	Allocation at the Point of Substitution
B2B	Business to business
B2C	Business to customer
BDE	Bundesverband der Deutschen Entsorgungs-, Wasser- und Kreislaufwirtschaft e.V. [Federation of the German Waste, Water and Raw Materials Management Industry]
BEW	Bildungszentrum für die Ver- und Entsorgungswirtschaft [Training center for the supply and disposal industry]
BMBF	Federal Ministry of Education and Research
BMUV	Federal Ministry for Environment, Nature Conservation and Nuclear Safety
CEDD	Cumulative energy demand – disposal/recycling
CEDP	Cumulative energy demand – production
CEDU	Cumulative energy demand – use
CO_{2eq}	Carbon dioxide equivalents
DIN SPEC	Consortium standard
DQL	Data quality level
EOL	End of life

EPS	Expanded polystyrene
EU	European Union
FU	Functional unit
GHG	Greenhouse gas
GVM	Gesellschaft für Verpackungsmarktforschung
GWP	Global warming potential
IK	Industrievereinigung Kunststoffverpackungen e.V. [German Association for Plastics Packaging and Films]
IML	In-mould label
IPCC	Intergovernmental Panel on Climate Change
ISCC	International Sustainability and Carbon Certification
KEA	Kumulierter Energieaufwand [Cumulative energy demand]
KIMW	Kunststoff-Institut für die mittelständische Wirtschaft NRW GmbH [Plastics Institute for Small & Medium-Sized Enterprises North Rhine-Westphalia Ltd.]
KRA	Kumulierter Rohstoffaufwand [Cumulative raw material demand]
KrWG	Circular Economy Act
kt	Kilotonnes (1,000 tonnes)
KUZ	Kunststoff Zentrum Leipzig [Plastics Center Leipzig]

LCA	Life cycle assessment
LCC	Life cycle costing
LWP	Lightweight packaging
MFR	Melt flow rate
MPO	Mixed polyolefin
NIR	Near infra-red light
OBRP	Ocean Based Recycled Plastics
PCR	Post-consumer recyclate
PE-(LD/HD)	Polyethylene (low-density/high-density)
PE-HMW	High molecular weight polyethylene
PET	Polyethylene terephthalate
PO	Polyolefin plastics
PP	Polypropylene
PS	Polystyrene
RAL-GZ	Quality mark of RAL Deutsches Institut für Gütesicherung und Kennzeichnung e.V. [RAL German Institute for Quality Assurance and Labelling]
REACH	Chemicals Directive on the Registration, Evaluation, Authorisation and Restriction of Chemicals
rPP	Recycled polypropylene
SKZ	South German Plastics Centre

SME	Small and medium enterprises
SVHC	Substances of Very High Concern
UZ	Eco-label
VerpackG	Packaging Act
VDI	Verein Deutscher Ingenieure e.V. [Association of German Engineers]
VDI TZ	VDI Technologiezentrum GmbH
VDI ZRE	VDI Zentrum Ressourceneffizienz [Centre for Resource Efficiency]
w/w%	Mass per cent

ABSTRACT

The recycling of plastics is a focus of the political and regulatory endeavours of the EU to promote the circular economy. According to the EU Plastics Strategy, all plastics placed on the market in the EU should be reusable or recycled in an economically viable way by 2030. In addition, the proportion of recyclates in plastics processing is to be considerably increased in order to boost demand for recycled plastics as well as to promote the economic viability of plastics recycling. The increased use of recyclates can also help to reduce Europe's dependence on crude oil imports and achieve the climate target of reducing greenhouse gas emissions by at least 55% by 2030. To this end, for example, the recycling rate for plastic waste set out in the German Packaging Act has been increased to 63% from 2022. In order to increase the reuse rate of recycled plastic waste in the packaging sector, it is also necessary to both improve the quality of the recyclate and adapt the requirements for the properties of the plastics used in packaging to the recyclate quality.

The first part of this study provides an insight into the status and prospects of plastics recycling in packaging plastics (especially polyolefins). To this end, the study begins with an overview of the current state of the art and innovations in plastics recycling. The opportunities and challenges for the use of recyclates in the packaging sector are discussed against the background of the political and regulatory framework conditions. For both the plastics processing industry and the users of plastic products (e.g. the packaging sector), developments in the circular economy represent an opportunity to intensify the use of recyclates. However, until a few years ago, it was possible to process plastic packaging waste only into inhomogeneous recyclates with varying compositions because of inadequate sorting and processing. Such low-grade recyclates are suitable for bulky products with low requirements for dimensional accuracy and dimensional stability. On the other hand, the closing of material cycles in the packaging sector requires the use of high-quality recyclates with a lower fluctuation range in their technical properties and minimal levels of impurities. Although the market availability of high-quality recyclates has so far been relatively low, considerable investments in the recycling sector are contributing to the development of a new market for high-quality recyclates. Against the background of political and regulatory requirements, this market is expected to grow strongly and result in better availability of high-quality recycled material.

The focus of this study is on a comparative ecological calculation and cost analysis of two packaging variants, one made from virgin plastic and the other from recycled plastic with approx. 5% virgin plastic[1]. Using a specific case study from the industrial production of high-quality packaging products (injection-moulded paint bucket with lid), the environmental impact of both materials (new polypropylene (PP) and recycled polypropylene) is compared.

The following research questions are analysed in detail:

(1) What energy requirement, expressed as “cumulative energy demand” (CED), can be attributed to the two packaging variants over their entire life cycle?

(2) What raw material consumption (expressed as “cumulative raw material demand” (CRD)) and water consumption can be attributed to the two packaging variants over their entire life cycle?

(3) What is the global warming potential, expressed in CO_{2eq}, of the packaging variants over their entire life cycle?

(4) What land requirements (forest areas, agricultural areas, settlement and transport areas, fallow, land and water areas)[2] must be taken into

[1] In the following, the declaratory addition “with a proportion of approx. 5% virgin plastic” is omitted for the selected packaging variant made from recycled plastic (paint bucket).

[2] Cf. VDI 4800 - 2: 2018-03.

account in the production of the packaging variants under consideration?

(5) What are the production costs of the packaging variants under consideration?

The result of the comparative life cycle assessment shows that the global warming potential (GWP) of the product made from recycled PP is 25% lower than that of the product variant made from virgin PP. In the base scenario analysed, the paint bucket made from PP recyclate has a GWP of 1.31 kg CO_{2eq} per functional unit (FU).[3] Meanwhile, the paint bucket made from PP virgin material achieves 1.74 kg CO_{2eq} per FU.

When comparing the cumulative energy and raw material demand according to the standard specifications of VDI 4800 - 2, the results show an even clearer savings effect: Within the system boundary under consideration and the selected allocation rules (cf. Chapter 3.2), the recyclate-based paint bucket has a cumulative total energy input (CED) of −2.9 MJ equivalents per functional unit. This is based on energy recovery through thermal recycling, which more than compensates for the energy demand for sorting and processing as well as the production of recyclate. Meanwhile, the bucket made from virgin PP has a CED of 25.3 MJ equivalents. This value is due to the energy demand for the production of virgin polypropylene, which is not counted towards the recycled materials. Although the energetic recycling of plastic waste based on virgin materials also results in a credit, only the use of recyclates in a second life cycle leads to an ecological advantage over the entire life cycle of the plastic.

In terms of water consumption over the entire life cycle, the product variant made from recycled material also performs considerably better than the variant made from primary plastic. The results show that the recycled

[3] **Comment: The result is subject to a certain degree of fluctuation because of the errors that occur and should therefore not be understood as absolute. As part of this study, a qualitative discussion of possible sources of error is conducted in Chapter 4.4.**

bucket only consumes a good third (around 2.46 l/FU) of the water used by a virgin material bucket (7.74 l/FU).

As part of a sensitivity analysis, the effects of the assumptions made regarding the allocation of environmental impacts between the first life cycle of PP (lightweight packaging) and the second life cycle (packaging made from PP recyclate) were analysed. In addition to the base scenario – in accordance with VDI standard 4800 - 2 – two further scenarios were tested. These address the current scientific discourse on the distribution of the environmental burdens between the first and second life cycle of plastic. In the 50/50 scenario, the environmental burdens and credits for PP primary production and disposal are distributed equally between the first and second life cycle of the PP. In the 50/100 scenario, it is a particularly unfavourable allocation for the recyclate because 100% of the CO_2 emissions from the incineration of the PP are allocated to the recyclate. Nevertheless, the results show that even under highly unfavourable assumptions, the use of recycled PP does not have a higher environmental impact than the use of virgin PP. In the 50/50 scenario, the GWP of the recyclate bin is almost on a par with the base scenario (1.33 kg CO_{2eq} per FU whilst the GWP of the recyclate bin in the 50/100 scenario is on a par with the virgin material variant. The use of plastic recyclates is therefore always advantageous from an ecological perspective.

From an economic point of view, the use of recyclate is not yet on a par with the use of virgin material if only the respective market prices for the raw material are taken into account. However, the case study considered here shows that it is perfectly possible to use recyclates economically for suitable applications. The cost analysis shows that different purchase prices for the two raw materials are the only variable cost factor in the production of a bucket made from recycled PP compared with a bucket made from primary PP. In this case study, the purchase price accounts for 54% of the total specific production costs for recycled PP and 62% for primary PP. All other operating costs can be assumed to be identically high. Because the use of high-quality recyclates does not require any investment in new injection moulding machines, there are no additional investment costs when switching to the use of recyclates. However, the use of special recyclates such as Ocean Based Recycled Plastics (OBRP) can lead to increased maintenance requirements for injection moulds – and thus to additional costs. At production sites for food packaging, care should be taken to physically separate the production lines for recyclate-based products because these are authorised only for non-food products (at least within the current legal framework).

Based on the results of this study, companies can emphasise the use of recyclates as a contribution to reducing resource consumption and protecting the climate. Even if PP recyclates cannot be described as "climate-neutral" because of their predominantly fossil-based raw materials, the use of these makes a major contribution to reducing the global warming potential of packaging – especially if recyclate-based packaging is functionally equivalent to packaging made from virgin material. In this case, packaging made from primary PP can be substituted; this, in turn, reduces the use of fossil raw materials such as crude oil.

This study consists of five chapters and begins by describing the object of investigation of the study as well as the objectives and research questions. Chapter 2 introduces the current market developments and the state of the art in plastics recycling of mixed lightweight packaging from household collections. In addition, the political and regulatory trends in connection with the desired circular economy are explained, and various solutions for the challenges of using recyclates are presented. Chapter 3 deals with the product analysed in the case study and explains the method used for the ecological comparative calculation and the economic evaluation. The results of the comparative life cycle, cost, and sensitivity analyses can be found in Chapter 4. The fifth chapter draws a conclusion from the results obtained and makes recommendations for improving the practical applicability of recyclates. It is aimed, in particular, at small and medium-sized companies in the plastics processing industry that are considering starting to use recyclates.

1 INTRODUCTION

1.1 The use of recycled plastics to produce new packaging

Plastics are versatile materials with outstanding processing and use properties. One of the most important areas of application for plastic materials such as polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET) is packaging. The universally mouldable material protects the products, ensures transport safety and efficient logistics, and enables an attractive presentation of the goods.

In Germany, the plastic consumption for packaging amounted to 3.17 million tonnes in 2020.[4] In the previous year, 3.16 million t of plastic packaging (> 95% of the quantity placed on the market) was recorded as waste (the fate of the remaining 5% is not known).[5] Of the plastic packaging waste collected in 2020, 1.91 million t were mechanically recycled. At over 1.24 million tonnes per year, the volume of plastic waste not mechanically recycled remains considerable. To date, this waste has been sent for energetic recycling.

Against the background of the climate neutrality target set by the EU for 2050[6] and the transformation to a circular economy by 2030, the extensive mechanical recycling of plastic waste is becoming increasingly important. In industry, the use of recycled plastics is an increasingly popular option for reducing the carbon footprint of products. Because the carbon contained in plastics is not initially released as CO_2 when they are mechanically recycled, recycling contributes to climate protection. Meanwhile, the Circular Economy Action Plan of the EU[7] formulates ambitious targets for the mechanical recycling of plastic packaging (cf. Chapter 2.4):

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[4] **Cf. GVM (2021), p. 15.**

[5] **Cf. Lindner, C. et al. (2020), p. 18.**

[6] **Cf. European Commission (2018).**

[7] **Cf. European Commission (2020).**

- The aim is to reduce (excessively expensive) packaging in order to minimise packaging waste.
- Packaging should be designed in such a way (design for recycling) that it is reusable and recyclable (e.g. by reducing the variety of materials).
- The use of recyclates is to be increased.

In accordance with the German Packaging Act of 2019, a recycling rate of at least 63% is to be achieved for lightweight packaging (LWP) from 2022. Although the rates for packaging plastics have risen in recent years (from 52.7% in 2000 to 60.5% in 2020) according to the Gesellschaft für Verpackungsmarktforschung (GVM)[8], high-quality mechanical recycling of plastic waste remains a challenge. The industry association of plastic packaging manufacturers[9] has set itself the goal of using at least 1 million tonnes of plastic recyclates per year by 2025; more than three quarters of these will be post-consumer recyclates (PCR).[10] For plastics processing companies (compound manufacturers), this raises the question of how they can adapt their production to the increased use of recycled plastics in light of new regulatory requirements and industry trends.

PET recyclates (especially PET bottles) obtained from LWP waste can already be managed in a closed loop. The mechanical recycling of plastics from mixed LWP waste is much more challenging. In some cases, these recycled plastics have a lower quality than the virgin material produced from crude oil or a lower security of supply.[11] Lower-quality plastic recyclates are suitable for simple applications such as park benches and turf grids.[12] This practice, also known as downcycling, contrasts with the

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8 **Cf. GVM 2021.**

9 **This is the IK Industrievereinigung Kunststoffverpackungen e.V. (German Association for Plastics Packaging and Films).**

10 **Cf. Schmidt, I. (2022).**

11 **Cf. Jetzke, T. and Richter, S. (2020), p. 1.**

12 **Cf. Verein Deutscher Ingenieure e.V. (2021).**

increasing demand for plastic recyclates for high-quality applications – and therefore higher quality – in the packaging sector.

Technical innovations and increasing expertise in the recycling sector and plastics processing industry have now contributed to a major improvement in the quality and availability of recyclates made from LWP waste. This opens up new possibilities for the high-quality mechanical recycling of recyclates for the renewed production of packaging, including packaging with high requirements in terms of dimensional accuracy and mechanical properties. Plastics processing companies already have access to a wide range of recycled materials in order to meet the increasing demand for products with recyclate content. This trend is likely to intensify because the establishment of a circular economy is both politically driven and socially desirable.[13]

Against the background of these developments, plastics processing companies must ask themselves whether and how plastic recyclates can be utilised for their respective manufacturing processes. This study provides a practical overview of the ecological and economic aspects of utilising plastic recyclates for the manufacture of high-quality packaging products as well as recommendations for plastics processing companies.

1.2 Object of investigation

Using a case study from industrial production, this study compares two specific plastic-based packaging variants: one that can be produced from a petroleum-based primary plastic and one with a proportion of recycled plastic. With regard to the dimensional accuracy and processing properties of the materials used, both products have equivalent properties in terms of quality and tolerance ranges. New plastics and recycled plastics differ mainly in colour and odour.

[13] **Cf. European Commission (2018).**

The study explains in detail the specific quality aspects associated with the use of recycled plastics. To this end, the standard processes for preparing for reuse (collection of lightweight packaging waste, processes for sorting and producing plastic recyclates) are first described in qualitative terms. The influence of various factors on the quality of plastic recyclates is then explained.

In particular, the importance of the sources of plastic waste used for recycling for the quality of the plastic recyclates produced from it is discussed here. In this context, the study addresses both technical and economic aspects that influence the existing manufacturing processes for plastic packaging when primary plastics are substituted by recycled plastics. In a broader sense, this also includes issues relating to the market acceptance of packaging made from plastic recyclates.

A sensitivity analysis is used to determine the ecological and economic effects this has on the manufacturing processes for the plastic recyclates themselves as well as the processability of the plastic recyclates in the existing manufacturing process for the selected packaging type.

1.3 Aims and research questions of the study

The ecological and economic comparative calculation is based on a specific application example of plastic packaging made from virgin plastic vs plastic recyclates. The following research questions are analysed in detail:

(1) What energy requirement, expressed as cumulative energy demand (CED), can be attributed to the two packaging variants over their entire life cycle?

(2) What raw material consumption, expressed as cumulative raw material demand (CRD), and what water consumption can be attributed to the two packaging variants over their entire life cycle?

(3) What is the global warming potential, expressed in CO_2 equivalents, of the packaging variants over their entire life cycle?

(4) What land requirements (forest areas, agricultural areas, settlement and transport areas, fallow, land and water areas)[14] must be taken into account in the production of the packaging variants under consideration?

(5) What are the production costs of the packaging variants under consideration?

In addition to clarifying the aforementioned research questions, the study also contains recommendations for small and medium-sized enterprises (SMEs) that process plastics and are considering starting to use plastic recylates. This study uses a case study to help evaluate the economic aspects, taking into account the market prices for recycled plastics.

[14] Cf. VDI 4800 - 2:2018-03.

2 STATUS AND PROSPECTS OF PLASTICS RECYCLING

2.1 Market relevance and market trends in plastics recycling and discussion of opportunities and challenges

2.1.1 Quantity and quality of plastic waste and recyclates

Quantities of plastic packaging waste

In 2021, total plastic consumption in Germany amounted to 12.4 million t. Of this, 3.2 million t of plastics were used for the production of packaging. Because packaging is a short-lived product, more than 98% of the packaging produced in the same year ended up as waste. In terms of total post-consumer waste, the proportion of packaging waste amounts to 59% or 3.2 million t. The total volume of plastic waste in 2021 was 5.67 million t, of which 5.44 million t were post-consumer waste and 0.23 million t were post-industrial waste. The post-consumer waste clearly dominates.[15]

Recyclate quantities

In 2021, 2.3 million t of plastic recyclate were processed in Germany. This corresponds to 16.3% of the total volume of plastics processed. Compared with 2019, the volume of recyclate used has thus increased by around 0.34 million t. Approx. 29% of the total volume of recyclates produced was used in the packaging sector. Higher recyclate use rates were achieved only in construction (approx. 40%) whilst lower rates were achieved in agriculture (approx. 11%), the automotive industry (approx. 3%), and the electrical industry (approx. 2%), amongst others.[16]

According to GVM (2020), the use of recycled plastic in packaging could be increased to around 0.96 million t per year. The plastics processing industry aims to use 1 million t of recyclates by 2025.[17] The fact that this is

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[15] **Cf. Lindner, C. et al. (2022), p. 16 f.**

[16] **Cf. Lindner, C. et al. (2022), p. 18 ff.**

[17] **Cf. IK Industrievereinigung Kunststoffverpackungen e.V. (2022), p. 1.**

not just a theoretical forecast is also reflected in the demand for recyclates. This increased by almost 20% between 2017 and 2019.[18]

Quality of plastic waste

In contrast to the determination of the quantities, the presentation of the quality of the plastic waste is much more difficult. In principle, the composition of the plastic waste has a major influence on the recyclates produced from it. The purer and more contaminant-free a waste fraction is, the easier it is to produce high-quality recyclates from it. Because of this, the origin of the waste (post-consumer or post-industrial) is a first indication of quality issues. For example, waste from the yellow bag is generally much more contaminated and heterogeneous than industrial waste.[19,20] A high proportion of mixed types of plastic and colours (especially black) as well as composite materials (increased inseparable layers of different materials) complicate the identification and separation of plastic waste in the sorting and recycling process. For this reason, mixed LWP waste from private households (post-consumer) is not yet mechanically recyclable.

Quality of recyclates

Until 2022, uniform quality standards for plastic recyclates had not yet been generally established in the plastics processing industry. In contrast to virgin plastics, the technical specifications of which are clear to users, the quality of recyclates generally varies. One reason for this is that the composition of the input materials for recycling, especially post-consumer LWP waste, is characterised by regional and seasonal differences. The properties of the recyclates available on the market are variable and their utilisation therefore requires a suitability test in each case.

The lack of consistency in material properties can, in turn, cause problems in machine control and product quality. For processing companies, this

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[18] **Cf. Scheuermann, A. (2021).**

[19] **Cf. Bendix, P. et al. (2021), p. 75.**

[20] **Cf. EU Recycling (2020).**

results in additional work for monitoring and, if necessary, readjusting the process parameters on the injection moulding machines. Fluctuations in the recyclate properties can be recognised during quality control on receipt of the goods. Processing parameters such as temperature and admixture of virgin material can thus be readjusted batch by batch. In the case of low-grade recyclates, the wall thickness of the packaging units to be produced (e.g. paint buckets including lids) may have to be increased. This adjustment can also adversely effect the mechanical properties. Against this background, the procurement of large batches of recyclates is more cost-effective because the cost of quality assurance is thus relativised. The long-term stable availability of recyclates with defined properties within predetermined tolerance ranges is therefore particularly important for high-quality target applications. In practice, plastics processing companies work closely with their suppliers in order to adapt the quality of the recyclates used to the individual target application.

However, the information offered by the various recyclate suppliers varies greatly. There is a lack of a standardised way of communicating information about the technical parameters of recyclates to market participants. Another problem is that the technical specifications of the recyclates provided by the supplier(s) cannot always be interpreted in such a way that they meet the requirements of the intended target applications. This means that recyclates of different qualities and prices can be used.

Because of the lack of standards, processors have to check the application individually for both virgin materials and recyclates. However, in the case of the latter, the question of whether the quality fulfils the requirements of the manufacturing process and the target application is more difficult to answer than in the case of virgin material. After all, the exact quality of recyclates can be defined only in combination with the specification of the product for which the recyclates are to be used.

As in the case of virgin material, the properties of recyclates are specified based on physical and technical parameters. This includes general information such as the shape and geometry of the recyclate and the appropriate manufacturing process. In addition, information is provided on physical properties such as density and melt flow index. Other important parameters for determining quality are optical and mechanical properties such as elasticity and impact strength. Compared with virgin material, the origin labelling (post-consumer vs post-industrial) is particularly important for recyclates because this provides an initial indication of quality. Odour is a typical characteristic of polyolefin recyclates made from post-consumer LWP waste; this differs considerably from virgin material. The high-quality recyclates currently available on the market have only a slight odour, which quickly dissipates when the end product is ventilated. Low-quality recyclates generally have an intense odour. It therefore depends on the target application as to how relevant individual aspects are for the final target group.

Table 1 provides an overview of the numerous parameters (including test standards/test methods) that can be used to describe both virgin and recycled plastics.

Table 1: Overview of material-specific test standards for PE and PP[21]

Property	Test method	PE	PP
Original use	To be specified by the sup-plier		
Form	Visual inspection	M	M
Recyclate content	EN 15343		O
Colour	Visual inspection	M	M
Particle size	ISO 22498	M	
Grain size distribu-tion	Standardised procedure		
Bulk density	Standardised procedure	M: Appendix B	O: Appendix A
Density	EN ISO 1183	O	M: EN ISO 1183-1 or Pro-cedure A
Fine grain content	Standardised procedure		
Degree of filtration	Mesh size	O	O
Filtration capacity	Standardised procedure		
Melt mass flow rate	EN ISO 1133	M	M: EN ISO 1133, Condition M
Dry flow rate	EN ISO 6186		
Vicat softening tem-perature	EN ISO 306		
Heat resistance	ISO 182-1, EN ISO 182-2, -3, -4		
Presence of foreign polymers	Fourier transform infra-red or differential scanning cal-orimeter	M (presence of PP and foreign polymers)	O
Presence of modified additives	To be specified by the sup-plier		
Foreign material	Standardised procedure		
Impurities	Standardised procedure	O: Procedure A, B, C, or D	Impurities
Content of volatile components	Standardised specification		O: EN 12099 or another
Water content/resid-ual moisture	DIN EN ISO 15512:2019-09	O	
Impact resistance	EN ISO 179-1, -2, EN ISO 180	O	M
Tensile stress	EN ISO 527-1 or -2	O	O

[21] Cf. Endres, H.-J. and Shamsuyeva, M. (2020).

Table 1: Overview of material-specific test standards for PE and PP further (continued)

Property	Test method	PE	PP
Elongation at break	EN ISO 527-1 or -2	O	O
Bending properties	EN ISO 178		O
Hardness	ISO 868		
Ash content	DIN EN ISO 3451	O	O
PVC content	Standardised procedure		
Polyolefin content	Standardised procedure		
Limiting viscosity	ISO 1628-5		
Alkalinity	Standardised procedure		

(M = required information; O = voluntary information; no information = empty cell)[22]

There are several ways to produce high-quality recyclates. On one hand, technical improvements in the sorting and separation can improve the quality of the recyclates produced from LWP waste. However, this requires further process engineering innovations and considerable investment. Another option would be to reduce the variety of materials in lightweight packaging in such a way that the purity of the input material (i.e. the LWP plastic waste collected) would be improved. Product manufacturers can make a decisive contribution here by considering the recyclability of their product as early as the development process (design for recycling). However, this requires regulatory measures, some of which are already provided for in the Circular Economy Action Plan of the EU. This can be achieved by minimising the variety of materials used and opting for mono-material solutions as well as by reducing the dyes used or rethinking the colour concept.[23]

It is also worthwhile for companies to promote the recyclability of their products in view of the Packaging Act and the plastics levy anchored in it. The plastics levy has been implemented in EU countries since 1 January 2021. Further details are explained in Chapter 2.4.4.

[22] Cf. Endres, H.-J. and Shamsuyeva, M. (2020).

[23] Cf. Bendix et al. (2021), p. 163.

Consortium standard DIN SPEC 91446

To assess the quality of plastic recyclates available on the market, those involved in the market along the value chain can use DIN SPEC 91446 "Classification of recycled plastics by Data Quality Levels for use and (digital) trading" published at the end of 2021 as a guide.[24] This consortium standard[25] enables consistent B2B communication about the qualities of recycled plastics (e.g. between recycling companies and compound manufacturers). The data quality levels defined in the standard describe a procedure for the specification of input streams and the calculation of the recycled content. A data sheet template defines the standardised description of data quality levels (DQL) for three categories of recyclate properties:

- Information (I): Characteristics of the collection, handling, and/or recycling process.
- Properties (P): Characteristics determined by a test according to a publicly available and defined standard.
- Optional characteristics (O): Voluntary information on plastic-specific technical properties.

These standardised descriptors make it easier for plastics processors to assess whether a recycled plastic could be suitable for a particular application.

Despite this newly established standard for the description of recyclate properties, an exchange of information between the suppliers of recyclates and plastics processors is still essential in practice. With a good understanding of the application purposes and manufacturing processes of their customer base, recyclate suppliers can ensure the long-term stable quality of the respective product line.

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[24] **Cf. DIN SPEC 91446.**

[25] **A consortial standard is a directive developed in a fast-track procedure that has not undergone the standardisation procedure (consensus requirement) that is otherwise usual for standards. The DIN SPEC according to the PAS (Publicly Available Specification) procedure are available free of charge.**

Eco-labels and certificates for products and users of recyclates

The environmental label DE-UZ 30a “Blue Angel for products made from recycled plastics” can be used for products with a minimum content of 80% by weight of recycled plastic (post-consumer recyclate).[26] It informs end consumers as well as commercial customers and public procurement about the ecological benefits of the labelled products. The award of the Blue Angel is intended to promote the sale of products made from recycled plastics in order to promote the mechanical recycling of post-consumer waste.

For finished products that consist of at least 90% plastic, authorisation to use the Blue Angel 30a eco-label can be applied for from RAL gGmbH [27]. The scope of application of this eco-label covers the following types of finished products:

- Office supplies (e.g. letter trays/drawer boxes)
- Waste and recycling bins
- Plastic buckets, pots, containers, and watering cans
- Seating groups or similar for outdoor use
- Palisades, fences, lawn grids, and playground equipment
- Compost silos and composters
- Film products.

However, plastic sales packaging and composite packaging are excluded from the scope of application.

When submitting an application, it must be verified that the respective product fulfils the award criteria for DE-UZ 30a.[28] In addition to specifying

[26] **Cf. Umweltbundesamt (2019).**

[27] **Exceptions are products with metal parts (e.g. carrying handles for buckets, steel arms, and wheel systems for barrels). These components are not included in the 90%- plastic content.**

[28] **Cf. RAL gGmbH (2019).**

a minimum proportion of 80% recycled plastic, the procurement regulation also sets requirements for limiting the pollutant content of the finished products. In particular, PCR materials may not contain more than 0.1% of substances of very high concern (SVHC) included in the REACH candidate list. Halogenated blowing agents or flame retardants as well as additives containing cadmium and lead and soft PVC are also not permitted. Other substances classified as hazardous in accordance with Annex VI to the CLP Regulation (for which there are hazard statements (H-phrases)) may not be added to the PCR materials either. Furthermore, the procurement regulation sets limits for the release of heavy metals from the products into the environmental media (water, soil).

For the award of the label, it must be demonstrated in the course of the application that the requirements of the award regulations are met. This includes an EuCertPlast certificate[29] on the origin of the plastic recyclates used. The evidence submitted is checked by an independent expert body at the production site and documented in a test report. Once the label has been awarded, confirmation of the recycled material supply chain must be submitted annually. In addition, the quality of the recyclates used must be ensured by random laboratory analyses and documented by means of corresponding test reports.

Another quality mark for labelling products with recyclate content is "RAL-GZ 720, % recycled plastic". It can be used for products that contain "recyclates from household recycling collections"[30]. The quality mark guarantees a consistent traceability of the recyclates throughout all stages of the recycling process for post-consumer LWP waste. The right to use the label can be acquired after joining RAL Gütegemeinschaft Rezyklate aus haushaltsnahen Wertstoffsammlungen e.V. based on the quality and test specifications for the percentage of recyclates.[31]

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[29] **Cf. Plastics Recyclers Europe (2018).**

[30] **RAL gGmbH (2020).**

[31] **Cf. RAL gGmbH (2020).**

For companies that use recyclates, ISCC certification (International Sustainability and Carbon Certification**)** is an option. ISCC is an independent, internationally recognised certification system for the proof of origin of industrially used raw materials along their entire value chain.[32] Originally developed for the certification of biomass, ISCC now also supports the mechanical recycling of plastics in line with the objectives of the circular economy. The ISCC PLUS certification guarantees a verified material origin by ensuring complete traceability of the recyclates along the entire recycling and supply chain. The use of all non-biological carbon-based materials, recycled waste, and residual materials can be certified under the ISCC PLUS certificate. It covers both pre- and post-consumer waste.

The ISCC PLUS certificate is used primarily as an instrument in B2B communication with business partners and stakeholders. The certificate is used in compliance with the ISCC requirements.[33] Companies wanting to use the ISCC logo or ISCC claims must first obtain authorisation from the ISCC.

In line with the specific requirements of the plastics processing industry, ISCC PLUS certification offers two chain-of-custody options:

- **Certified physical segregation:** The certified product must contain recycled plastic from traceable sources. The recyclates are physically separated from virgin material along the entire value chain. Physical separation enables clear statements on the recycled content that relate directly to the origin (e.g. “the product is made from recycled-based raw materials certified according to the ISCC standard”[34].
- **Mass balance method:** Products can contain a mixture of new and recycled plastics. The guaranteed proportion of recycled plastics is certified in order to avoid double counting.

[32] **Cf. ISCC (2022).**
[33] **Cf. ISCC (2022).**
[34] **ISCC (2022).**

With both options, a sustainability declaration must be issued for all outgoing materials. Certificate holders must ensure that all incoming and outgoing delivery documents contain the necessary information in accordance with the ISCC requirements.

2.1.2 Price trends for virgin materials and recyclates

When making statements about the price development of recyclates, it is important to differentiate between secondary applications (e.g. pipes made from PE recyclate) and packaging applications.

Recyclate prices for secondary applications[35] have long been linked to primary raw material prices. A value of around 80% of the price of virgin material was previously used as a rough guide for the market price of recyclates. Crude oil prices collapsed in 2020 and 2021. This created price pressure on the recycling industry for the first time. The temporary availability of virgin material at a more favourable cost put financial pressure on many recycling companies because the demand for recyclates fell because of the low prices for virgin material, and the ongoing recycling processes no longer covered their costs. However, since 2022[36], recyclate prices have been once again increasing in comparison with virgin material. The further development remains to be seen.

Meanwhile, market prices for high-quality recyclates (e.g. for packaging applications) have not collapsed because the quantities available on the market can barely meet demand. This is not least due to the lack of availability of unmixed plastic waste for recycling. Improving the quality of LWP plastic waste (e.g. through recycling-friendly packaging design) is a long-term trend that, from a current perspective, does not yet offer sufficient investment security for those processing plastic waste. Uncertainty about the future availability of suitable input materials therefore

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35 **Areas of application without high quality requirements for the recyclates include products such as flower pots, garden furniture, pipes, and pallets.**

36 **Last updated: October 2022.**

represents an obstacle to the expansion of processing capacities and, as a result, to the availability of high-quality recyclates on the market.

PE recyclates that are suitable for packaging applications were priced at EUR 300/t (fraction from sorting) in 2020. In 2021, the price fell to EUR 200/t. In 2022, prices rose again, in some cases to over EUR 500/t. Experts expect that the price of recyclates in high-end applications such as packaging will rise to three to four times that of virgin material in the next few years.

From the perspective of plastics processing companies, the foreseeable price trend for high-quality recyclates is the same, albeit for different reasons.[37] As a result, demand for recyclates will continue to increase and be reflected in rising market prices. It can be assumed that recyclate prices will remain at a high level for the time being because the supply side will not be able to meet the demand for high-quality recyclates to a sufficient extent. Current investments in modern sorting and processing plants are not expected to lead to a fall in the price of recyclates for at least two to four years.

However, it is difficult to make a long-term forecast of the price trend for recyclates. In this context, government regulations (e.g. recyclate quotas for beverage bottles) as well as voluntary commitments by manufacturing companies to use recyclates are stimulating demand for high-quality recyclates.

2.1.3 Availability and procurement of recyclates

In addition to technical and regulatory requirements that need to be fulfilled or complied with, the availability of recyclates is currently a limiting factor (cf. Chapter 2.1.2). Two established procurement channels for purchasing recyclates with defined quality criteria are listed below.

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[37] **Cf. Schmitz, M.; Dengel, G.; Karsubke, H. (2022).**

Manufacturers of recyclates, compounds, and virgin materials

Many recyclates are now available as standardised branded products and can be purchased directly from the relevant recycling companies and compound manufacturers.[38] Although companies that want to use recyclates no longer have to do pioneering work, it is important to build up individual expertise with regard to recyclate processing and formulations. It is not possible to make generalised statements about these aspects because they always depend on the respective target applications and target group requirements. In practice, a close dialogue with suppliers is therefore recommended. They are often well placed to assess the requirements for the recyclates resulting from the corresponding target application. The basic prerequisite for this is a common understanding of quality, the plastic processing procedures, and the product requirements that need to be fulfilled.

In addition to recycling companies and manufacturers of compounds, manufacturers of virgin material (*virgin plastics*) are increasingly offering their own recyclates or virgin material with recycled content.[39]

Digital platforms

The Industrystock search engine provides an initial overview of the range of recyclates available.[40] This allows recyclates and compounds to be filtered directly by country and delivery type as well as other categories such as colour master batches or functional additives. In addition to direct business relationships with selected recyclate and compound manufacturers, such platforms offer another good opportunity to source plastic recyclates and gain an initial overview of the market. The focus is on bringing together stakeholders along the value chain, creating transparency, building trust, and improving the continuous transfer of material data. Selected platforms on the market are briefly presented below.

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[38] **Cf. Schmitz, M.; Dengel, G.; Karsubke, H. (2022).**

[39] **Cf. Schmitz, M.; Dengel, G.; Karsubke, H. (2022).**

[40] **Cf. Industrystock (no date).**

(a) Plastship[41]

Plastship was the first European marketplace for recycled plastics and still provides suppliers and buyers with a tool for trading secondary plastics.[42] For example, plastics processing companies can filter by material type (e.g. regranulate, compound, and regrind), by polymer (PE-HD, PE-HMW, and PE-LD), by colour category (e.g. transparent, blue), by processing method (e.g. injection moulding, and extrusion), recyclate definition (e.g. MFR), delivery location, distance, and other criteria. The additive/master batch selector can also be used to search for the right additives for the respective application.[43][44] The services of the platform services are continually being developed. By the end of 2023, work will continue on a further function that identifies potential recyclate application areas by critically examining and reclassifying existing factory standards and general norms.[45] This is intended to counteract the fact that various standards and norms prevent the use of recyclate even though this would be possible in terms of product technology.[46]

(b) Cirplus[47]

Cirplus is another platform that supports the procurement and sale of recycled plastics. Here, plastics processing companies can search for suitable offers and use the respective filter options: Material type (e.g. recyclate, plastic waste), supply (e.g. ongoing, one-off), source (e.g. post-industrial, post-consumer), material type (e.g. PE-LD, PE-HD, and PET), condition (e.g. granulate, bales), colour (e.g. transparent, blue), DIN SPEC

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[41] **Cf. Plastship GmbH (no date).**
[42] **Cf. Plastship GmbH (no date).**
[43] **Cf. EU Recycling (2020).**
[44] **Cf. Plastship GmbH (no date).**
[45] **Cf. SKZ (2022/2023).**
[46] **Cf. Bendix et al. (2021), p. 168.**
[47] **Cf. Cirplus GmbH (no date).**

91446 (e.g. DQL1, DQL2), certificates (e.g. DIN 14001, DIN 9001), quantity, and price (min and max. values) as well as country.

(c) Second Trade[48]

Second Trade is another B2B platform for secondary raw materials. Recyclers from all over Europe can offer secondary raw materials here. Interested buyers from all countries can view and purchase the offers. In order to ensure the highest possible level of security for all parties involved, only tested and verified partners have access to the platform. Sales are based on the best bidder principle (i.e. raw materials are offered at a minimum price and sold to the highest bidder). In contrast to the two platforms mentioned above, the range of plastics available on Second Trade is limited in terms of material selection. Only the plastics polystyrene and polyurethane are currently available.

(d) Further services and services of digital platforms

In addition to providing a marketplace for plastic recyclates, some online platforms (e.g. Plastship or Cirplus) offer further services in order to make it easier for plastics processing companies to use recyclates. These range from the manufacture to the disposal of the products. Companies are supported in making their products more recyclable. Selected services are listed below:

- **Product analysis:** The product is analysed with regard to recyclability. The focus here is on identifying obstacles and opportunities for mechanical recycling as well as options for optimisation.
- **Process analysis:** Based on the recycling processes established on the market, options for mechanical recycling are being developed.

[48] Cf. Secondtrade GmbH (no date).

- **Recycling partnership:** The recycling process is implemented within the framework of recycling partnerships that originate from the network of the platform (in this case Plastship).
- **Implementation:** In order to successfully implement a recycling concept, operational and logistical challenges need to be overcome. On request, the platform-operating companies can take over the management and development of all necessary resources.

2.2 State of the art and innovations in the recycling process for plastic waste from lightweight packaging

2.2.1 Collection and sorting of waste streams

LWP collection

In Germany, licensed plastic LWP is collected in yellow bags and bins. This usually also includes other non-packaging (recyclables) of the same material. The collection is carried out by companies on behalf of the dual systems, which take the collected LWP to the sorting plants.

LWP sorting

In order to separate the used lightweight packaging from households (which is collected separately in the dual system) as accurately as possible, several process steps are required. Conventional LWP sorting has gradually evolved since the introduction of the dual system. The small plants, which were initially mainly characterised by manual sorting, developed into the current largely mechanised and automated large-scale plants with a total throughput of over 120,000 t/a (corresponding to approx. 4 million residents). In addition, there has been extensive standardisation of both the basic procedures used and the process sequence.[49]

[49] **Cf. Umweltbundesamt (2021).**

Now, a distinction is essentially made between two groups: LWP sorting plants with plastic type sorting in which the dimensionally stable plastic packaging (e.g. trays, bottles, cups, and cans) is separated according to polymer type and older plants without PC sorting, which are essentially characterised by smaller throughputs of less than 40,000 t/a.

The function of LWP sorting within the respective process cascades can be characterised as follows: Packaging is allocated to specific groups for subsequent material-specific processing. This means that individual components of packaging are not broken down in the LWP sorting process nor is the sorting process completed in the procedural sense. Rather, pre-concentrates are produced from a technical point of view. In the practice of LWP sorting, the intended targeted allocation of packaging is therefore largely dependent on the final design of the overall packaging. In terms of its composition, it leaves the process stage essentially in the same way as the consumers have placed it in the separate collection system.

The sorting methods used can be generalised based on a general flow chart. The arrangement of individual process steps and the corresponding sorting technologies vary from plant to plant (cf. **Figure 1**), whereby the main components of an LWP sorting plant – in accordance with the state of the art – are as follows:

(a) **Conditioning** of the input material using a container opener and metering machine

(b) **Classification** into three to five grain sizes using drum and oscillating screens

(c) **Sorting** into different material and plastic fractions using magnetic separators, eddy current separators, air separators, sensor-supported NIR sorting systems, ballistic separators, and manual picking.[50]

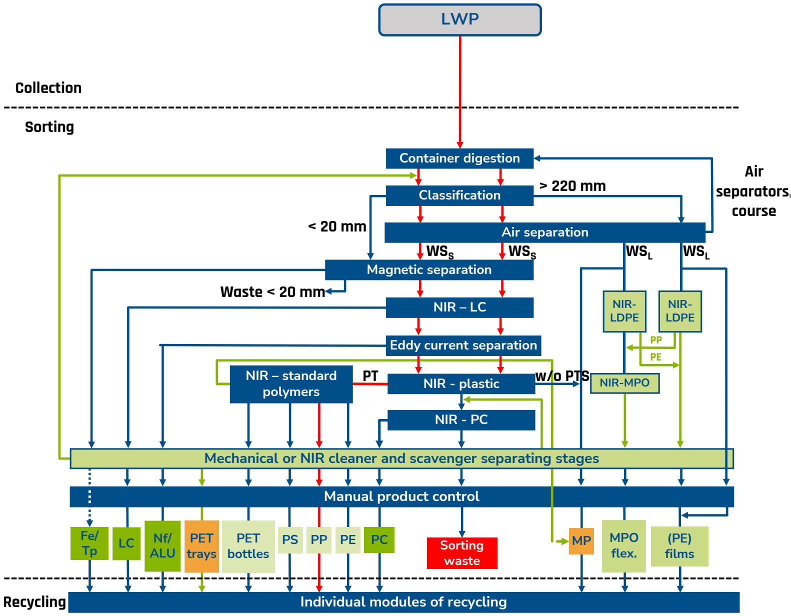
[50] **Cf. Knappe et al. (2021), p. 52.**

In addition, Figure 1 shows the path from PP-based “dimensionally stable” packaging to the PP fraction (marked with red arrows) in preparation for Chapter 3. Furthermore, the sorting fractions to be assigned to mechanical recycling are highlighted in green; an orange background indicates a predominantly energetic recycling and a red background indicates an obligatory energetic recycling.

The first step is container digestion (conditioning) in which both larger collection sacks and smaller bin liners have to be broken down. In the next step, the resulting mixture passes through a screen classification (grading). Mainly drum screens, which fulfil several functions, are used for this purpose:

- Emptying of the torn open bags
- Homogenisation of the volume flow
- Distribution over several lines if necessary (symbolised by the parallel arrows in Figure 1)

Classification narrows the size range in order to improve the conditions for the efficient sorting and pre-enrichment of packaging groups.



Legend

Sorting fractions
ALU – aluminium fraction; FE – ferrous metals; LC – liquid cartons; LDPE – Low Density Polyethylen; LWP – lightweight packaging; MP – mixed plastics; MPO – mixed polyolefin, Nf – non-ferrous metals; NIR – near infra-red; PE – polyethylene; PET – Polyethylenterephtalate; PS – polystyrene, PP – polypropylene; PC – paper/cardboard; Tp – tinplate

Other
flex. – flexible; PT – plastic types (HDPE, PP, PS, PET-A); w/o PTS – without plastic type sorting,

Figure 1: Schematic representation of LWP sorting © Institut Cyclos-HTP GmbH

A functional separating cut of 220 mm is standardised in the systems. In older systems for the separated plastic films (roughly equivalent to DIN A3 format), this defines the boundary between film fraction with allocation for regranulation and mixed plastic fraction for predominantly energetic recycling in advance. Classification is also to be regarded as a sorting stage with regard to the lower separating cut because the screened fine material may be discharged as sorting residue after metal separation. This step is relevant for the classification of smaller portion packs (e.g. coffee cream cups), which in modern systems are usually retained for the subsequent sorting operations in the course of fine screening using a long-hole mesh (approx. 20 × 40 mm). In older systems, screening is still sometimes carried out at 50–60 mm; non-metallic small packaging is then effectively unsortable.

The fine classification of the “20 mm screen cut” is always achieved in two stages using a combination of a drum screen and an oscillating screen.[51] The oscillating screen is fed with the screen throughput from the upstream drum screening machine, which has a width of 50 mm. The oscillating screening machine is designed in such a way that a stream of material that is approximately free of packaging is discharged as sorting residue in its screen throughput. The screen overflow of the oscillating screen (20 to 50 mm) is reunited with the screen overflow of the drum screen at a suitable point (cf. Figure 2).

The illustration shows the screen deck of the oscillating screen machine with the slotted hole covering described at the top left. To the right are the two outgoing conveyor belts with the material flows 20–50 mm (upper belt) and fine grain < 20 mm (below). Typical components of the 20–50 mm fraction are objects such as coffee capsules, screw caps, lipstick tubes, and crown caps made from various materials. In contrast, the finest fraction < 20 mm is visually dominated by the EPS abrasion.

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[51] **The process was developed in 1997 by the engineering company HTP.**

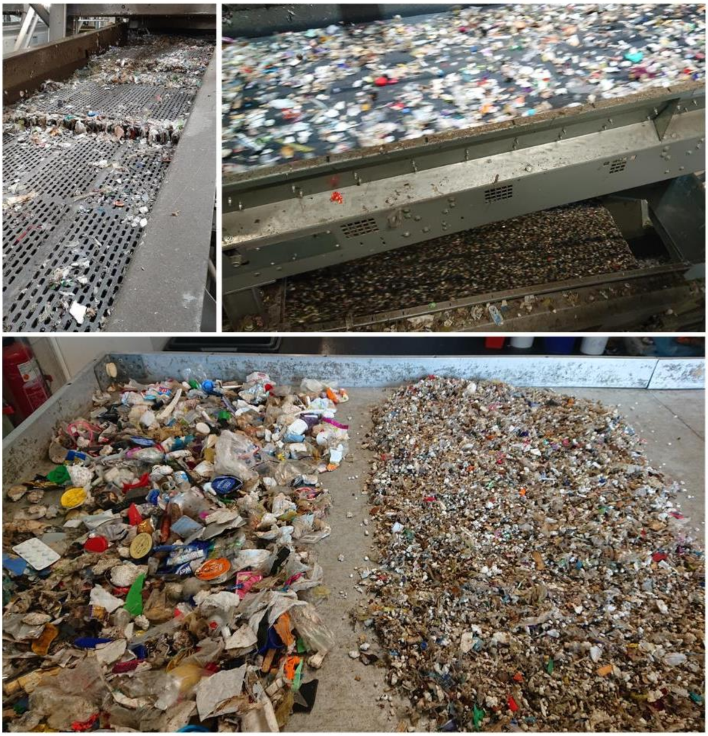

Figure 2: Illustration of the results of fine screening in LWP sorting © Institut Cyclos-HTP GmbH

This is followed by further mechanical and process-related sorting of the materials according to their different physical properties (sorting). Air separation to separate plastic films is followed by magnetic separation. The separating feature here is the magnetic susceptibility (or magnetisability) of the material. All packaging with ferromagnetic properties is separated with a high degree of efficiency. In addition to tinplate cans and crown caps, this includes packaging in which steel is used as a secondary component (e.g. in composite cans with a tinplate base).

In the next step, liquid cartons are sorted out. Only sensor-supported sorting machines based on the principle of near-infra-red reflection measurement (hereinafter referred to as "NIR separators") are used for this purpose.

Aluminium packaging is sorted out downstream using eddy current separation. The separating feature here is the electrical conductivity. In the technical implementation, the deflection of the conductive materials takes place in the outlet of a high-speed conveyor belt. There is thus an overlap with the ballistic influencing variables. Aluminium packaging and aluminium composites can be sorted out with a high degree of efficiency using eddy current separators. Most composite packaging that contains aluminium foil as a barrier layer (e.g. soup bags, squeeze packs, tubes) is also transferred to the aluminium fraction during sorting using eddy current separators.

The eddy current separation is followed by the sorting of the dimensionally stable (three-dimensional) plastic packaging – either as mixed plastics, as an MPO partial stream, or as a collective separation stage for further plastic type sorting. Despite the differences in the extent of differentiation by polymer type, only NIR separators are used for the initial separation of plastics from the mixture. This applies to all 3D plastic sorting products with the exception of Fractions 322 (buckets and canisters > 5 l), 325 (PET bottles), and 321 (PO bottles)[52], which are separated manually in individual cases of little relevance. The PP fraction is usually separated as the first plastic sorting fraction within the polymer cascade, mechanically post-cleaned, and pressed after control sorting.

Finally, paper packaging and paper composites are sorted out. NIR separators are also predominantly used for this purpose. In smaller, older-generation systems, this separation stage is not always automated.

Until the end of 2018, the handling of lightweight materials, which mainly consist of plastic film, from the air separation of individual screen fractions

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[52] **Cf. Duales System Deutschland GmbH (2017).**

was regulated in a relatively standardised manner as part of the sorting contracts. Film fraction 310 was produced from the upper separating cuts (cuts > 220 mm) after manual re-sorting. The remaining size classes were allocated to mixed plastics – in the case of plants with MPO production, to the dimensionally stable polyolefinic plastic packaging of Fraction 323. Because of the increase in recycling rates through the VerpackG (Section 16), initial sorting concepts have been modified to generate a higher proportion of mono-fractions in the flexible packaging sector. These are better tailored to the requirements of high-quality mechanical recycling.

Because the traditional formula “film > DIN A4 ≙ LDPE film” is valid only to a limited extent and the qualified sorting of smaller formats requires the implementation of NIR separators to sort out PE, the film lines in the latest generation systems have also been equipped with NIR separators. Corresponding conversions were also carried out in some older large-scale plants. This means that LDPE films and (PP-enriched) MPO-flex (323-2) can already be produced in several plants instead of (large-format) films and mixed plastics.

Output fractions of LWP sorting

According to the current state of the art, the process sequence of functional process components makes it possible to convert recyclable materials into more than 10 recyclable fractions. The output proportion of the PP fraction at the end of the sorting system corresponds to approx. 6% of the LWP input quantity and approx. 12% of the production quantities of plastic fractions. The yield (i.e. the product fraction in relation to the polymer content in the input) for the different fractions is shown in table 2.

Table 2: Sorting yield in relation to the polymer content in the input[53]

Material flow from LWP/recyclable sorting	Yield of the product fraction in relation to the polymer content in the input
PE	52 w/w%
PP	49 w/w%
PS	48 w/w%
PET	95 w/w%
Films (> DIN A4)	32 w/w%

The required purity of the individual sorting fractions is defined by the product specification of the dual systems. In accordance with the specifications of the dual systems, purities of 94 w/w% must be achieved for the PE, PP, and PS fractions. However, these requirements are usually not met for the individual fractions in the current mechanical sorting of LWP. In practice, only the PE fraction fulfils this requirement. PP and PS are lower at 86 w/w% and 78 w/w% respectively.[54] The situation is similar for the PET and film fractions. According to the specification, these should have purities of 98 w/w% and 92 w/w% but reach 75 w/w% and 88 w/w%.[55]

Problems and challenges are identified less in the sorting process than in the actual collection of waste from households. Because the waste separation behaviour of citizens, 25–30% of the recyclable plastic packaging is lost (i.e. some of it is disposed of in the residual waste bin). Meanwhile, the actual sorting process results in maximum losses of 5%.

2.2.2 Processing and regranulation of the recyclable fractions

The separated recyclable fractions from the sorting process (cf. Chapter 2.2.1) are then subjected to further processing steps in order to produce high-quality recyclates with defined properties. For the mechanical recycling of plastic waste, the dry/wet mechanical process has established

[53] Cf. Knappe et al. (2021), p. 53.

[54] Cf. Bulach, W. et al. (2022), p. 30.

[55] Cf. Knappe et al. (2021), p. 53.

itself in practice. The focus is on the separation of contaminants such as paper, glass, and foreign plastics as well as the removal of dirt and impurities. Figure 3 shows the dry/wet mechanical process.

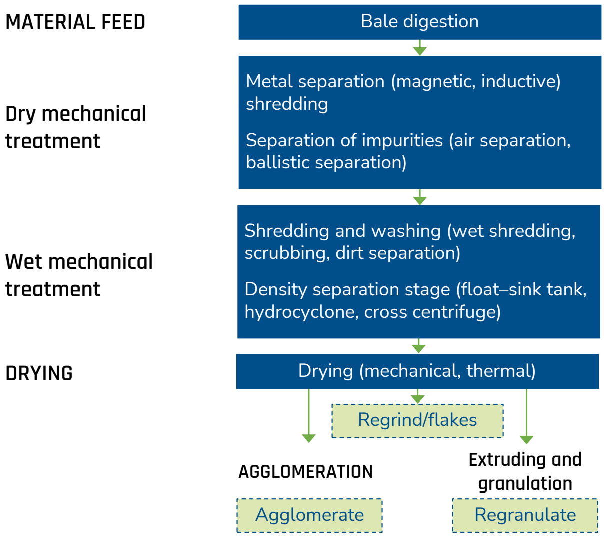

Figure 3: Schematic representation of the dry/wet mechanical process for plastics processing according to the state of the art[56]

The following simplified process description takes into account all the key process steps of the actual recycling process. At the abstraction level considered here, the different system configurations can be represented in a single basic process with a sub-variant.

[56] Own illustration from VDI Centre for Resource Efficiency (2023), p. 27.

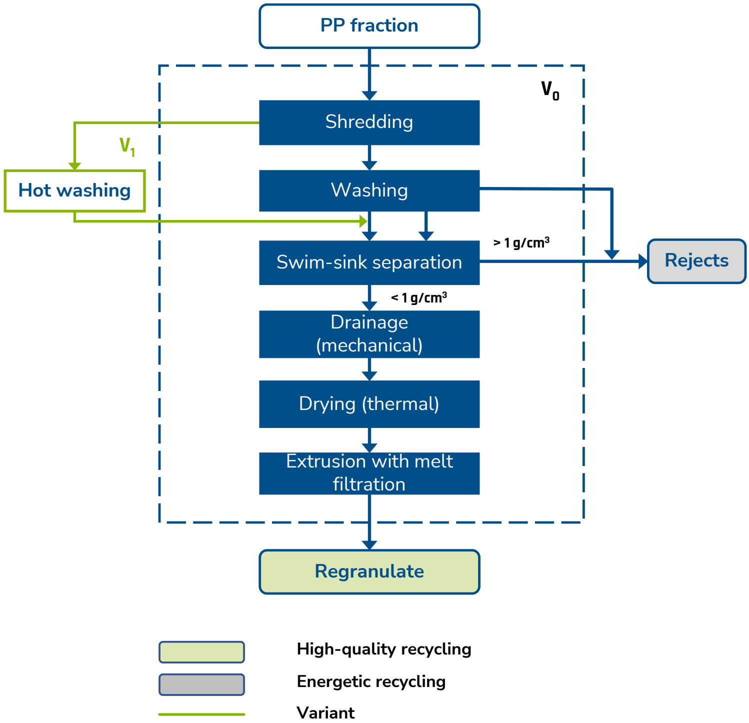

Figure 4: Simplified process flow diagram of PP recycling © Institut Cyclos-HTP GmbH

Figure 4 shows the basic procedure of the treatment process described below (V0) with the hot wash variant (V1) shown. The qualities of the PP sorting fraction provided by the sorting plants are delivered and temporarily stored as large bales as standard. The actual processing begins with the pre-shredding of the large bales with downstream magnetic separation to separate the binding wire. In the standard process sequence, fine shredding is then carried out using granulators.

In Figure 4, pre-shredding and fine shredding are summarised as shredding. The aim of shredding is to produce regrind with a size of approx. < 10 mm as a prerequisite for the functionality of the subsequent separation and transport. The subsequent washing process is generally not carried out as a hot wash and does not involve the addition of surfactants or other detergents. Non-polyolefinic plastic particles are separated by means of float-sink sorting (gravimetric sorting in water) at a separation density of 1 g/cm³. The process principle of density separation can be implemented in different types of machines or sorting units (e.g. float/sink tanks, sorting centrifuges, and hydrocyclones). Non-polyolefinic plastic particles enter the sinking material and are discharged as “rejects”. The polyolefin mixture enriched in the floating material is dewatered, dried (if necessary), and re-melted using an extruder. Depending on customer requirements, additives such as master batch and chalk are added. After extrusion with melt filtration and, if necessary, homogenisation of the regranulate produced, the sales units are supplied in Big Bags, octabins, or silos.

A medium to dark grey regranulate is produced in the basic version (cf. Figure 5; other dark colours can also be produced by adding pigments). This regranulate is marketed for the production of plastic pipes as well as various injection moulding applications. Improving the quality of PP recyclates to expand the range of applications requires additional steps. The colour sorting upstream of the shredding and the colour sorting of the regrind enable a partial stream to be used also for lighter, more colour-sensitive applications. The second is hot washing to improve surface cleaning (in particular to remove label adhesives).

This is a prerequisite for decontamination processes using vacuum extraction; these can be used to produce rPP for cosmetics packaging, among other things. In practice, decontamination via vacuum extraction can be achieved only after upstream hot washing. To date, two PP recycling companies in Germany have integrated hot washing systems

Figure 5: rPP regranulate (left: dark grey basic variant, right: black pigmented) © Öko-Institut/Andreas R. Köhler

There are also solvent-based separation processes such as the Vinyloop, CreaSolv, and Newcycling processes. However, for economic reasons, these separation processes have not yet been established on an industrial scale in Germany.[57]

2.2.3 Information options on the use of recyclates for plastics processing companies

For companies that want to process recyclates, comprehensive expertise regarding suitable qualities, the mixture of formulations, and processing technology is essential. However, basic research in this field is no longer necessary. For example, companies can acquire knowledge through training centres and courses or work together with system manufacturers, compound manufacturers, and other service providers. In addition to the relevant knowledge, the development of a positive mind-set towards the use of recyclate is particularly important for those involved along the value chain.

Training centres and courses

Comprehensive expertise is essential in the procurement and use of recyclates. The range of corresponding training courses is continually

[57] **Cf. Knappe et al. (2021), p. 72.**

increasing but is still at a rather low level. Some research and educational institutes offer courses on the use and processing of recyclates. These the Kunststoff Zentrum (KUZ) in Leipzig, the Kunststoff Institut Lüdenscheid (KIMW), and the Süddeutsche Kunststoff-Zentrum (SKZ) in Würzburg.

In addition, a few other organisations also offer training opportunities. Examples include the Federation of the German Waste, Water and Raw Materials Management Industry (BDE), the Training Centre for the Utilities and Waste Management Industry (BEW), the Association of German Engineers (VDI), and the Fresenius Academy.

System manufacturers and manufacturers of recompounds

Increasingly more system manufacturers for injection moulding machines are now ideally positioned with regard to the processing of recyclates (e.g. injection moulding of sandwich components). Some of these companies also offer comprehensive consulting and training services. Digitalisation also plays a key role in the circular economy. For example, in the "injection 4.0" programme, Engel Austria has developed a digital solution that specialises in batch fluctuations. All details can be found on the respective company websites.[58]

In addition to the companies that manufacture the systems, manufacturers from whom recyclates and recompounds are purchased are also suitable contacts when it comes to clarifying questions about suitable qualities, the mixing of formulations, and processing technology. In practice, there is often close contact and intensive dialogue between suppliers and plastics processing companies. This interaction is therefore important in order to adapt the qualities to the respective specifications of the products and to develop customised solutions.[59]

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[58] Cf. Engel Austria (no date). Krauss Maffei is another example.

[59] Cf. Schmitz, M.; Dengel, G.; Karsubke, H. (2022).

2.3 Presentation of the technical parameters for the production of new packaging from recycled plastics

When processing recyclates in the injection moulding process, the viscosity, which represented as the melt flow rate (MFR), is a decisive parameter. The viscosity must be low (high MFR value) so that the material has the right flowability for processing in a modern injection moulding process. In modern injection moulds, an MFR value of more than 45 g/10 min is required in order to be able to use processing methods with short cycle times for the manufacture of thin-walled products.[60] Impurities and fillers in the recyclate can lead to an increase in viscosity – and thus to a reduction in the MFR. This has an unfavourable effect on the processability of the recyclates in injection moulding. Recyclates with a low MFR are therefore not suitable for the manufacture of thin-walled products. In order to be able to process these, a blend must be produced.[61] The MFR for thermoplastics is usually determined according to DIN EN ISO 1133; in rare cases, DIN 53735, which has already been withdrawn, is still used.[62]

Other important parameters include all mechanical parameters such as elongation at break and tensile elongation or notched impact strength. For high recyclate qualities, the formulation must be adapted depending on the input material. Blends with up to 100% recyclate content are possible with LWP waste from sources with unmixed commercial collection (e.g. catering). In contrast, post-consumer recyclates (PCR) from household collection in dual systems can generally be processed into high-quality applications such as paint buckets only if a gradual proportion of virgin plastic is mixed in. In practice, RAL blends (with quality mark “RAL-GZ 720, % recycled plastic” (cf. Chapter 2.1.1) contain 30–90% PCR recyclate.[63] For high-quality applications such as paint buckets, a high recyclate content of over 90% can also be achieved by setting up a closed recycling loop (e.g.

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[60] **Cf. Maschinenbau-Wissen (2009).**

[61] **Cf. Schmitz, M.; Dengel, G.; Karsubke, H. (2022).**

[62] **Cf. Endres, H.-J. and Shamsuyeva, M. (2020).**

[63] **Cf. Schmitz, M.; Dengel, G.; Karsubke, H. (2022).**

in the form of an individual take-back system). A 100% recyclate content is also possible with PCR from mixed LWP waste; however, this requires more complex sorting in the recycling process, and the price of the recyclate increases.

Odours from recyclates were – and still are – an interference factor that can affect the market acceptance of products made from them. This applies in particular to PCRs produced from mixed LWP waste without additional cleaning steps. The odours originate primarily from the migration of former filling materials (e.g. meat or dairy products), paints, and adhesives into the plastics. In the meantime, some PCR suppliers have optimised their recycling processes to such an extent that the unpleasant odours of the recyclates are barely noticeable[64]. These usually disappear just a few minutes after unpacking the product.

Another possible interference factor in the injection moulding of PCR is the evaporation of volatile components that are produced by the chemical conversion of the polymers during heating. In order to minimise these, continuous quality control of the PCR materials and the use of a process air purification system are advisable. However, this also applies to the processing of virgin material. Hazardous substances (SVHC) may not be contained in packaging applications.

Although PCR from recycled LWP waste does not usually contain any REACH-relevant additives, this may well be the case with other sources of recyclable materials such as recyclates from waste electrical and electronic equipment. However, the risk of such impurities in recyclates has been steadily decreasing.[65]

[64] **Cf. Ministerium für Klimaschutz, Umwelt, Energie und Mobilität Rheinland-Pfalz (2022).**
[65] **Cf. Schmitz, M.; Dengel, G.; Karsubke, H. (2022).**

2.4 Political and regulatory framework conditions for the use of recycled plastics today and in the future

The recycling of plastics is increasingly becoming the focus of political and regulatory measures at the European level. Not least against the background of climate targets, the aim is to reduce the use of fossil primary raw materials in plastics production, among other things. The environmentally friendly disposal of plastic waste – in particular used lightweight plastic packaging – is also a major problem because of the large quantities that accumulate. Plastic LWP not disposed of properly can enter the environment and accumulate there because it hardly decomposes. In the long term, packaging waste therefore contributes enormously to the pollution of the environment with microplastics.

Against this background, the mechanical (re)recycling of LWP plastic waste is high up in the waste hierarchy because it helps to minimise the aforementioned problems. For this reason, the recycling targets in the Packaging Act have been raised, among other things. Nevertheless, the mechanisms of the free market alone are not yet sufficient (cf. Chapter 2.1) in order to provide appropriate incentives for the extensive recycling of mixed LWP plastics. As a result, the recycling rates for PCR plastic waste tend to fall short of the regulatory targets in practice. This is another reason why there are currently various regulatory initiatives at the EU level. In addition, the plastics industry has launched voluntary initiatives to increase the utilisation of recycled material from PCR plastic waste. The most important policy initiatives are briefly outlined in the following sections.

2.4.1 EU Plastics Strategy and Single-Use Plastics Directive

On 3 July 2019, the EU Plastics Strategy came into force as Directive 2019/904/EU on the reduction of the impact of certain plastic products on the environment (Single-Use Plastics Directive). With their help, the basis for a new plastics economy is to be created. It specifically addresses the following topics:

- Reuse, repair, and recycling
- Promotion of the development of more sustainable materials
- Promotion of the market for recycled plastics

The aim of the strategy is for all plastics placed on the market in the EU to be reusable or economically viable for recycling by 2030. In addition, the recyclate content in plastics processing is to be substantially increased. In addition to excluding non-recyclable materials from plastic packaging, there is a great need to increase the sorting, treatment, and processing of plastic waste.[66,67]

2.4.2 EU Packaging Directive (EU-VerpackRL)

The Packaging Directive (EU-VerpackRL) came into force on 4 July 2018 as part of the EU waste package. It is based on the EU Packaging Directive 94/62/EC introduced in 1994; under this directive, the EU member states have defined measures to reduce packaging waste and its environmental impact. The renewal of the directive is intended to promote the transition to a circular economy. The innovations relate to the following areas:

- Waste prevention
- Recycling and reuse
- Waste recycling and disposal

Specifically, the updated EU Packaging Directive stipulates that EU member states should increase the recycling targets for packaging waste, increase the proportion of reusable packaging (and its actual reuse), and create incentives for the application of the waste hierarchy. A recycling target of 50 w/w% by 2025 and 55 w/w% by 2030 has been set for plastic packaging waste. Requirements are also placed on the design of packaging. These should be designed in such a way that they can be reused in an

[66] **Cf. BMK (no date).**

[67] **Cf. Umweltbundesamt (2018).**

environmentally friendly way without compromising food safety or consumer health.[68,69]

2.4.3 EU Circular Economy Action Plan

The Circular Economy Action Plan was adopted on 11 March 2020 as an important element of the European Green Deal, the European agenda for climate neutrality and sustainable growth. It forms a (legal) framework for sustainable product policy and aims to make European production and consumption both climate-neutral and competitive. It contains three essential components:

- Measures for product design
- Measures to strengthen the position of consumers
- Measures for more sustainable manufacturing processes.

Plastics are one of the seven product value chains in the focus of the action plan. The overarching goal is to increase the mechanical recycling of recycled plastics. Important fields of action here include the introduction of a mandatory recyclate use quota in the areas of packaging, building materials, and vehicles as well as pricing for every kilogramme of plastic waste that is not recycled. The latter policy objective has already been implemented in the form of the EU plastics levy (cf. Chapter 2.4.4).[70,71,72,73]

2.4.4 EU plastics levy

The EU plastics levy on non-recycled plastic waste came into force on 1 January 2021. This has created an incentive for EU member states to reduce packaging waste and promote plastic recycling in the interests of the

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[68] Cf. DR Deutsche Recycling Service GmbH (no date).

[69] Cf. EU-VerpackRL (2018).

[70] Cf. NABU (2020), p. 3.

[71] Cf. European Commission (2020).

[72] Cf. IHK (no date).

[73] Cf. Mederake et al. (2020), p. 24.

circular economy. The amount of non-recycled plastic waste is defined as the difference between the weight of packaging waste generated in a particular year and the amount recycled in the same year.

Non-recycled plastic packaging waste is subject to a charge of EUR 0.80/kg. For the time being, the transfer amounts incurred are still being financed from the respective national budgets of the member states. As a result, Germany transfers EUR 1.3 billion in tax money to the EU every year. However, it can be assumed that an adjustment will be made in favour of the polluter pays principle. In concrete terms, this means that it will no longer be the state that pays the levy but rather the packaging manufacturers or the companies placing the products on the market.[74,75,76,77,78]

2.4.5 German Circular Economy Act (KrWG)

The Circular Economy Act (KrWG) transposes the EU Waste Framework Directive and individual provisions of the EU Single-Use Plastics Directive 2019/904/EU into German law and was passed on 1 June 2012. With the amendment of the EU Waste Framework Directive in 2018, the Circular Economy Act was also amended and re-enacted on 29 October 2020. The aim of the law is to promote the circular economy through waste avoidance and waste recycling. The following regulatory instruments are primarily used for this purpose:

- Product responsibility and duty of care
- Prohibition of mixing and separate collection obligation
- Voluntary return
- Obligations of the public sector

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[74] **Cf. VerpackG (2019).**

[75] **Cf. European Commission (2021).**

[76] **Cf. Hesselmann Service GmbH (2022).**

[77] **Cf. IHK (2020a).**

[78] **Cf. EUWID (2021).**

Specifically, the Circular Economy Act contains requirements for individual waste streams, an increase in reuse and recycling rates, and a new regulation on the end of the waste characteristic.

In addition, the previously three-stage waste hierarchy has been expanded to include "preparation for reuse", "recycling", and "other recycling" (cf. figure 6).[79],[80,81,82,83,84]

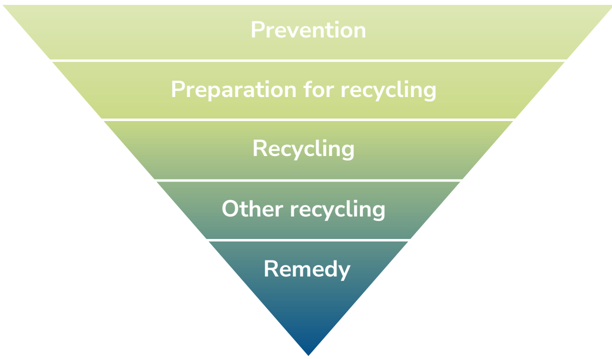

Figure 6: Waste hierarchy in accordance with the Circular Economy Act[85]

2.4.6 Packaging Act (VerpackG)

The German Packaging Act (VerpackG) has been transposing the EU Packaging Directive 94/62/EC into German law since 2019. The law was amended in 2021. Since 3 July 2021, the VerpackG has been implementing both the EU Single-Use Plastics Directive and the EU Waste Framework Directive into German law. The law is intended to prevent or reduce the

[79] Cf. BMUV (2021).
[80] Cf. BMUV (2020).
[81] Cf. IHK (2020b).
[82] Cf. Umweltbundesamt (2022a).
[83] Cf. Mederake et al. (2020), p. 13.
[84] Cf. Turuc, A. (2021), p. 14.
[85] Own illustration from VDI Zentrum Ressourceneffizienz GmbH (2022).

environmental impact of packaging waste. It applies to all packaging placed on the market in Germany and regulates the following processes:

- Placing of packaging on the market
- Return, provision of information, and proof of packaging waste
- High-quality recycling of packaging waste

The Packaging Act provides for different measures depending on the type of packaging, material fraction, and area of use (B2B/B2C). For example, manufacturers, retailers, and importers who place B2C packaging subject to system participation on the German market for the first time must join a (dual) system and register with the Central Agency Packaging Register (ZSVR) foundation.

The registration obligation will apply to all manufacturers of packaging filled with goods from July 2022. Companies that place particularly large quantities of packaging on the German market for the first time and are subject to system participation must also have a declaration of completeness certified once a year on the quantity of packaging placed on the market in the previous year and submit it to the ZSVR. Initial distributors and subsequent distributors of B2B packaging must take back similar packaging waste free of charge and recycle it properly. This applies also to reusable packaging. In addition, manufacturing companies can voluntarily label their products with the European recycling codes (recycling cycle, packaging material, material group) in order to provide information about the plastic fraction of their packaging.[86,87]

Recycling rates, recovery rates, and minimum recyclate content

VerpackG stipulates that at least 90 w/w% of plastic packaging must be recycled. From 1 January 2022, at least 70 w/w% of this recycling rate must be achieved through mechanical recycling. In addition, the recycling

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[86] **Cf. VerpackG (2019).**

[87] **Cf. Turuc, A. (2021), p. 22.**

rate for plastic waste has been increased to 63 w/w% since 2021. For single-use plastic beverage bottles, a minimum recyclate content of 25 w/w% will apply from 2025 and 30 w/w% from 2030.[88,89]

Various stakeholders in Germany and the EU are calling for minimum quotas for the recyclate content in plastic products. Two different approaches are used: product-specific recyclate utilisation quotas and material- or polymer-specific substitution rates. In addition to recyclate use quotas, price control mechanisms are being discussed.[90]

2.4.7 Industry initiative of Industrievereinigung Kunststoffverpackungen e.V. (German Association for Plastics Packaging and Films)

The German Association for Plastics Packaging and Films (IK) recommends the use of recyclate for packaging and calls on companies that manufacture and use plastic packaging to use 1 million t of recyclates per year in Germany by 2025. This will require an additional 500 kt of recyclates. However, plastic recyclates are not yet available on the market in the desired quantities, and high qualities in particular are rare.

The IK therefore recommends the consistent implementation of eco-design and recycling-friendly design for plastic packaging in order to increase the quality of input materials for mechanical recycling. A toolbox for inspiration for recycling-friendly eco-design is freely available on line. The freely accessible web tool "Recyclass" can be used to assess the recyclability of plastic packaging.[91]

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[88] **Cf. Recycling Service GmbH (no date).**

[89] **Cf. Industrystock (no date).**

[90] **Cf. IK e. V. und AGVU (2020).**

[91] **Link to the Recyclass on-line tool: https://recyclass.eu**

2.5 Challenges and solutions for the use of recyclates

The BMBF-funded DiLink project has empirically analysed **barriers in the plastics recycling value chain** and identified the following obstacles to the use of recyclates:[92]

- Lack of trust in recycled plastics and the recyclers.
- Lack of knowledge about the qualities and properties of recyclates.
- Lack of transparency regarding material properties.
- Lack of data availability and lack of data exchange with regard to reliable recyclate availability

In addition, the following aspects often complicate the use of recyclate in practice:[93]

- strict requirements for the quality of products made from recyclates
- low price advantage of recyclates compared with virgin material with simultaneous additional costs for procurement and quality testing on the demand side

At present, the biggest obstacle to the use of recyclates is the limited availability of high-quality grades. Because of the sharp rise in demand for recyclates, there is a shortage on the supply side, thereby resulting in a price increase. According to experts, the recyclate price will most likely remain at a high level until the supply side can adequately meet the demand side.

Batch fluctuations and inhomogeneity of the recyclates are further obstacles. Not only between different batches but also within a batch, variations in the plastic processing procedure can occur with PCR because of different qualities. By selecting suitable recyclate sources with as homogeneous an input stream as possible, products with almost equivalent properties to

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[92] **Cf. DiLinK (2020).**

[93] **Cf. DiLinK (2020).**

virgin material can be achieved. The task of process management and quality control is to cushion such fluctuations and, ideally, to take direct countermeasures if necessary. This is possible with appropriate in-line measuring methods. These measurements are taken during the production process. Corresponding measuring equipment continuously records data, thereby enabling continuous process monitoring. In the event of deviations from the target value, direct countermeasures can be taken in this way. Unlike previously used off-line measurement methods such as testing specimens or components in the laboratory, this modern technology can control the process parameters of injection moulding machines in real time. This opens up scope for tolerances in the materials used, which also makes it easier to process recyclates. For example, the research institute SKZ – German Plastics Centre developed a new in-line measuring system for detecting foreign particles in the plastic melt and launched it commercially in 2021. Ultrasound and radar-based test systems for the in-line detection of non-metallic and metallic foreign materials greatly reduce quality losses in the finished component.[94,95]

Non-product additives pose a further challenge with regard to the use of recyclate. If recyclates from other areas of application are used, the additives they contain may interfere with or even prevent their use in the target application. Standards to be complied with and target group requirements to be fulfilled can also represent an obstacle to the use of recyclate.

In view of the difficulties faced by plastics processing companies in connection with batch fluctuations and inhomogeneities in the aforementioned recyclates, various research and innovation projects are currently underway. Digital solutions based on artificial intelligence (AI) are being developed to facilitate the exchange of information between recyclate production and application.

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[94] **Cf. SKZ – Das Kunststoff-Zentrum (2021c).**

[95] **Cf. Keyence (2023).**

The BMBF-funded project “Circularity Optimisation for Plastics” (CYCLOPS) is developing AI-based data processing and analysis methods based on a “digital twin” for secondary raw materials.[96] As an extension of “cirplus”, the existing on-line trading platform for recyclates (cf. Chapter 2.1.3), this AI system is intended to enable a user-friendly assessment of the properties and processing options of recyclates. The aim is to create a transparent exchange of information – including technical characteristics and quantity forecasts for different raw material qualities and their ecological performance – in the recycling loop for plastics.

The aim of another BMBF-funded project, “SmaKuRez”, is to develop a smart service system database for plastic recyclates. This should considerably simplify the use of post-consumer recyclates for plastics processors.[97] For this purpose, application-related recyclate qualities are defined and categorised into application classes. The project defines and records the quality and performance criteria for various areas of application for plastics. The resulting database will enable plastics processing companies to determine suitable recyclate blends and process parameters for specific products and manufacturing processes and then document them for quality assurance purposes. In addition, certified, ready-mixed and additivated recyclate mixtures with 30–100% recyclate content are being developed. Furthermore, an on-line tool called Rezy-Spezi is being developed; this is to be implemented with the “Plastship” trading platform (cf. Chapter 2.1.3).[98] This tool is intended to provide a standardised assessment basis for the use of recyclate in various areas of application.

The “PlasticBOND” research and cooperation project, which is also funded by the BMBF, involves the sustainable optimisation of plastic packaging through development projects on detailed material knowledge and digital services.

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[96] **Cf. Werner. J. (2021).**

[97] **Cf. Kunststoff-Zentrum SKZ (2021a).**

[98] **Cf. Achenbach, H. (2022).**

The project is divided into three programmes:

- Assessment of environmental sustainability
- Process and material analysis
- Cooperation models in digital value creation networks.

The aim is to establish a B2B platform that enables life cycle assessment along the plastics processing value chain as a result of data exchange within the network.[99]

The AI application hub for plastic packaging, which is funded by the BMBF, consists of two innovation labs. KIOpti-Pack is concerned with the holistic, AI-based optimisation of plastic packaging with recyclate content with a focus on design and production. K3I-Cycling is working on the AI-supported optimisation of the recycling of plastic packaging. Fifty-one associates from business, science, and society are cooperating in this endeavour, thereby pursuing the goal of sustainably closing the plastic packaging value chain through an intensive exchange of data and results.[100]

The cross-company and cross-sector consortium R-Cycle was founded in 2020. The 30 members are working together on an open and globally applicable traceability standard (digital product passport) in order to enable seamless documentation and traceability along the value chain for recyclable packaging.[101]

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[99] **Cf. PlasticBOND (2022).**

[100] **Cf. KI Hub Kunststoffverpackungen (2023).**

[101] **Cf. R-Cycle (2023).**

3 METHODOLOGICAL CONCEPT OF THE STUDY

3.1 Ecological and economic assessment methods

The methodological concept of the life cycle approach or product life cycle assessment (LCA) is used for the scientifically based evaluation and comparison of the ecological and economic aspects of the choice of materials for product packaging. This allows the most relevant positive and negative environmental impacts of a product system as well as economic indicators to be analysed transparently. Considering the entire product life cycle ensures that the assessment includes all significant influencing factors.

Possible conflicts of objectives and problem shifts are thus recognised; for example, environmental impacts between the individual stages of the life cycle and between different environmental aspects or environmental media. Because of the processes taken into account, the life cycle approach is also known as the cradle-to-grave approach.

This study uses a target group-orientated adaptation of the standard life cycle assessment methodology; this is tailored to the information needs of SMEs. Applying the general procedure for life cycle assessments according to the DIN EN ISO 14040/14044 standard, the ecological impact assessment is also based on the standards VDI 4600 and VDI 4800 - 2.[102]

The economic evaluation of the packaging variants analysed in the study is also based on the life cycle approach and relates to the same functional unit. For this purpose, a comparative cost analysis is carried out, taking into account the investment and operating costs (in EUR). These are determined by calculating all costs associated with the product under consideration; these are borne directly by one or more actors in the life cycle of this product.[103] This includes costs along the entire value chain and use

[102] Cf. DIN EN ISO 14040:2006.
[103] Cf. Hunkeler et al. (2008).

phase through to disposal.[104] Using a direct comparison of the objects of investigation, it can be determined which option performs best overall from an economic point of view as well as from the perspective of a particular actor (in this case, the target group of SMEs). It is also possible to determine the period in which necessary investments are amortised or where the break-even point can be located.

The methodological principles for carrying out cost analyses are anchored in various international and national standards and directives for different applications.[105] Some aspects are also covered by conventional investment costing methods.

3.1.1 Models for ecological impact assessment

Recognised indicators that evaluate the environmental impact are used for the comparative assessment of the packaging variants. These are based on scientifically verified calculation models, which are briefly explained below:

Global warming potential (GWP), carbon footprint

The “global warming potential” indicator refers to the weighted sum of all climate-relevant GHG emissions over the entire life cycle of the products analysed. The GHG amount has the unit carbon dioxide equivalent (CO_{2eq}) and is referred to as the carbon footprint. It describes all greenhouse gas emissions that can be directly or indirectly attributed to the life cycle stages of products. Greenhouse gases in the sense of this definition are not only carbon dioxide but also gases for which the Intergovernmental Panel on Climate Change (IPCC) has defined a coefficient for global warming potential (GWP). Because these gases each have a different impact on the climate, all relevant greenhouse gases are converted to carbon dioxide equivalents (CO_{2e}). The current assessment method ReCiPe 2016

[104] Future cash flows are typically discounted, taking into account both inflation rates and typical interest rates.

[105] Cf. ISO 15663-2:2001.

Midpoint (H) from the GreenDelta method pack V 2.1.2 for openLCA is used to analyse the global warming potential. This method uses the current IPCC values to convert all relevant emissions into CO_2 equivalents.[106]

The product-related total GHG amount results from the allocation of all material and energy flows inventoried in the life cycle inventory to GHG emission factors; these are recorded in scientifically verified databases. Specifically, the individual calculation steps for allocating the life cycle inventory to climate-relevant emissions are carried out using life cycle assessment software.

Cumulative energy demand (CED)

The cumulative energy demand (CED) is an indicator of the sum of the different primary forms of energy used directly or indirectly in a product throughout its entire life cycle in order for it to fulfil its function. For this purpose, the energy consumption associated with production (CEDP), utilisation (CEDU) and disposal/recycling (CEDD) is calculated and totalled in accordance with the calculation specifications of the VDI standard 4600:2012-01 standard.

For the calculation, a mass and material balance is first created for each of the packaging variants under consideration based on the inventory data provided. This is then linked to CED data from relevant databases (cf. Chapter 4.1). In addition to the presentation of the total CED as the sum of the individual contributions, the cumulative energy demand from renewable energetic resources ($CED_{renewable}$) and the cumulative energy demand from non-renewable resources ($CED_{non\text{-}renewable}$) are also shown as subtotals.

The methodology from VDI standard 4600 “Cumulative energy demand (CED) – Terms, calculation methods” is used to analyse the cumulative energy demand. This includes the renewable energy sources biomass, water,

[106] Cf. IPCC (2021).

wind, solar radiation, and geothermal energy as well as the exhaustible fossil and nuclear energy sources. Adding up the above energy sources gives the total CED.

Cumulative raw material demand (CRD)

Rules for balancing the cumulative raw material demand (CRD) are set out in VDI standard 4800 - 2. To balance the CRD, "all primary raw materials required to provide the benefit within the balance limits are quantified. Secondary raw materials are taken into account only with their transport and processing costs".[107] Appendix A of VDI standard 4800 - 2 contains tabulated CRD values in t/t for a number of mineral and metallic raw materials.

Water consumption

The current evaluation method ReCiPe 2016 Midpoint (H) from the GreenDelta method pack V 2.1.2 for openLCA is used to analyse the water consumption of the two paint bucket variants to be compared.

3.1.2 Models for economic evaluation

The cost analysis identifies all relevant costs (expressed in EUR and in relation to the functional unit) associated with a specific product; these are borne directly by one or more actors in the life cycle of this product.

Operating costs (e.g. costs for operating materials, maintenance, and disposal)

Based on the operating costs, a direct comparison of different objects of investigation can be used to determine which variant represents the most economical option overall from the perspective of one or more specific actors (in this case, the target group of SMEs). It is also possible to determine

[107] VDI 4800 - 2:2018-03.

the period in which necessary investments are amortised or where the break-even point can be located.

3.2 Scope of the study

The scope of the study describes the product system to be analysed and its functions as well as the upstream and downstream processes to be considered throughout the entire product life cycle. This ecological comparative calculation compares two variants of the packaging product "polypropylene paint bucket" with the same filling quantity. The basic function or benefit of the compared product variants is to provide ready-prepared wall paint for commercial and private end use at the point of use (e.g. on construction sites or for renovation work). The focus of this study is on analysing the influence of the materials used – virgin polypropylene vs recycled material – in order to evaluate the ecological and economic performance of the paint bucket variants. The scope of the study therefore also takes into account the recycling processes for producing the polypropylene recyclate.

3.2.1 Description of the packaging variants analysed

The packaging variants to be examined represent two functionally identical types of paint buckets with a filling volume of 10 l (cf. Figure 7). Both variants are mono-material products (i.e. they consist almost entirely of polypropylene (PP)).

- Jokey mono-material bucket (JETO+ 110-01) made from 100% PP virgin material
- Jokey mono-material bucket (JETO+ 110-01 REC) made from LWP-based PP-recyclate with approx. 5% virgin PP content

Figure 7: Schematic representation of the JETO+ 110-01 paint bucket system of Jokey SE © Jokey SE

3.2.2 Functional unit

In the course of the ecological and economic comparative calculation, the associated material and energy flows as well as the cost data must be assigned to a standardised reference value. A functional unit is defined for this purpose. ISO 14040 describes the functional unit as the quantified benefit of a product system for use as a reference unit.[108] The functional unit must correspond to the objective and the scope of the study. In this case, this means that it enables a direct comparison of the ecological and economic key figures of the packaging variants under consideration. For this reason, all corresponding material and energy and energy input and output quantities (reference flow) over the entire life cycle of the packaging are allocated to this reference value.

Functional unit

Production of attractive packaging for the retail market for the safe and durable storage, transport, and use of wall paints in a standard commercial container size of 10 l.

To derive the functional unit for the packaging variants under investigation, the individual functional characteristics were systematically analysed. This was done using the information provided by Jokey. The main purpose of plastic packaging is to protect the packaged contents. This function

[108] Cf. DIN EN ISO 14040:2006.

includes not only the storage and handling of the packaged product during storage, transport, and distribution but also its safe use by the end consumer. Packaging also fulfils a marketing function. Another functional element of packaging is information about the contents. This is clearly visible on the packaging surface in the form of a label or coating.

3.2.3 System boundary of balancing

The definition of the scope of the study includes the clear presentation of the system boundary (i.e. a description of the processes considered in the study (cf. figure 8) throughout the entire life cycle of the two packaging var-iants).

The calculations presented in this study are based on the assumption that the different packaging variants basically have the same utilisation characteristics with regard to their function during filling, transport, cooling, and use. The product intended for filling the paint buckets (i.e. the wall paint) is therefore not taken into account in this study because its properties have no influence on the comparison of the packaging variants. The life cycle stages of filling and use are part of the scope of the study. However, the related sub-processes (e.g. transport) are excluded from the calculation (grey background) because they are identical for both packaging variants.

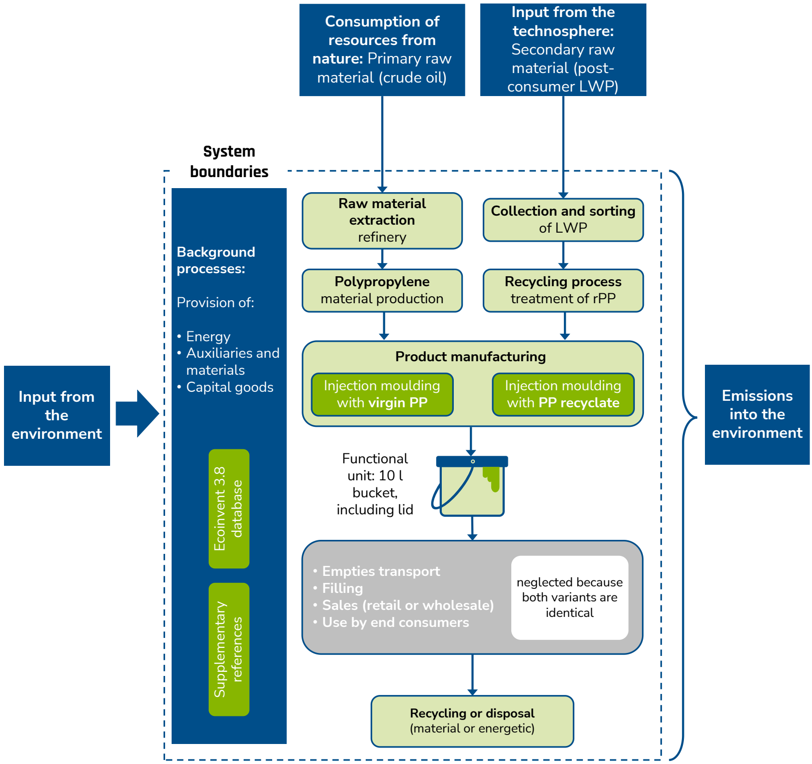

Figure 8: Overview of sub-processes within the system boundary considered in the case study © Öko-Institut

The following life cycle stages of the paint buckets were taken into account:

- Extraction of raw materials from nature and their further industrial processing into raw materials and energy sources for the bucket made from primary raw materials and the collection and sorting of LWP for the bucket made from secondary raw materials
- Manufacturing process (material production and recycling process) of buckets with handle and separate lid (one lid is needed for each bucket, the ratio of buckets and lids produced is 1:1)

- Disposal and recycling of the buckets (end-of-life phase, energetic recycling)

The following life cycle stages and processes are **not taken into account**:

- Production facilities and infrastructure (e.g. production of recycling systems and injection moulding machines or transport vehicles)
- Transport processes of empty paint buckets to the filler, including the use of outer and transport packaging
- Production of the filling material (wall paint)
- Application phase at end users, including shopping trips and storage It was assumed that there are no differences between the packaging variants analysed

3.2.4 Allocation rules

The allocation rule is the term used to describe the methods for allocating the environmental impact and possible credits. The allocation rule to be used can have a considerable influence on the result of the LCA. Their definition is therefore based on a comprehensive system understanding of the plastics recycling and manufacturing process.

If joint products are produced in the manufacturing process, the environmental impacts determined in the LCA must be divided accordingly between the main product and the by-product. Joint products are all products that are not waste (i.e. have a positive market value). No joint products are known in the production of the packaging variants analysed here. There is thus no need for allocation in the manufacturing process of the paint buckets. However, in addition to polypropylene recyclate, the upstream recycling process for lightweight packaging waste also produces many other fractions (e.g. metals, cellulose, other plastics), which are considered joint products. This is based on a mass-based allocation rule (i.e. the environmental impacts of the individual recycling steps are allocated to the output fractions according to their mass percentage). In addition, the reuse of recycled materials requires the definition of allocation rules for the environmental impact of producing virgin materials on the first and second life cycle. The same applies to credits resulting from thermal waste treatment.

In the case of the polypropylene recyclate used, the environmental impact determined was allocated to the first and second life cycle stages of the plastic considered here. Because the origin of the PP recyclate from LWP waste suggests the first life cycle of PP as a packaging material, the prevailing disposal practice for most LWP waste (thermal recycling) was taken into consideration. The assumptions[109] made in other studies and information from the expert interviews were also taken into account here.

The base scenario (0/100) therefore specifies that the recyclates from LWP do not bear any environmental burdens (0%) from the original production of the LWP and the credits and environmental burdens (100%) from the final recycling after use. The first (original PP-LWP) and second (PP recyclate) life stages are considered separately. For the PP recyclate, the "cut-off rule" is applied (cf. Table 11). This is in line with VDI standard 4800 - 2, which stipulates that no credits from the original life be made with the aim of honouring the actual raw material demand.

[109] Cf. Dehoust et al. (2016), p. 43ff.

Table 3: Structure of the base scenario

	1st life cycle: original PP LWP	2nd life cycle: PP recyclate
Base scenario (0/100)		
Environmental impact from the production of original PP-LWP from virgin material	100%	0%
Environmental burdens and credits from recycling after 2nd life cycle (EoL)	0%	100%

3.2.5 Requirements for data quality and origin

Data quality

In order to create the database required for the study, certain requirements are placed on the data collected. In general, both specific and generic data were used. In line with standard practice in life cycle assessments, specific data were collected for the processes in focus (e.g. recyclate extraction and injection moulding of paint buckets) using questionnaires:

- LWP sorting and mechanical recycling process in the dual systems
- Production data for the paint bucket and corresponding lid[110]

Generic data generally comes from LCA databases and other literature sources as well as from information provided by experts interviewed. Generic data from literature and the Ecoinvent v3.8 database[111], which was the current version at the time of the study, were used for the upstream chains of the virgin material and energy sources used to manufacture the paint buckets. Ecoinvent was chosen as the data basis because the database contains a broad availability of data sets relevant to the present study.

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[110] Cf. Jokey SE (2022).

[111] Cf. Ecoinvent (2022).

In addition, these data can be used consistently with regard to system boundaries and impact assessment and are available in comparatively detailed and transparent documentation.

The ecological comparative calculation to be implemented was modelled as an “attributive life cycle assessment”. Accordingly, only data records that originate from the “Allocation at Point of Substitution (APOS)” system model of the Ecoinvent database or that follow a system logic that methodically corresponds to this allocation approach were used.

The data and data quality requirements define the characteristics of the data required to carry out a LCA in general terms. The generic data sets used from the databases were selected in such a way that they were as close as possible to the materials and processes found in the system to be analysed. In addition, a temporal and spatial reference to the object of investigation of this study was established. The requirements on which this study is based are summarised below:

- **Time-related scope of application:** In this study, the data used on upstream and downstream chains reflect the representative average state of the art. This means that both the primary and the specific data should not be older than two years. The secondary datasets from Ecoinvent v3.8 refer to different time spans. The Ecoinvent database was last updated in 2021.
- **Spatial scope of application:** The geographical reference area is Germany, particularly at the level of bucket production and end-of-life processes. Data records from the Ecoinvent v3.8 database were used for the provision of preliminary products and materials (e.g. production of plastic granulates or chemicals). It was assumed that these were raw materials purchased on the world market. Therefore, unless specified more precisely, global data sets that relate to average market conditions were used.

- **Technological coverage:** The primary and specific data used generally reflect the current state of the art in 2022. The latest IML production line from Jokey at the Wipperfürth site was examined. The end-of-life scenarios correspond to the current technological practice at the LWP plastics recycling companies in Germany.

Data source

The data on the LWP recycling process (collection, sorting, and recycling) is based on studies on the dual systems[112]. In addition, interviews with experts were conducted. The data on weights and material composition as well as the production of the paint buckets are based on primary data from Jokey. The reference period for the production data of Jokey is between 2021 and 2022. The data on the end-of-life treatment of the paint buckets is based on studies on the dual systems.

3.2.6 Cut-off criteria

When preparing a LCA, highly complex processes are often analysed and data collected. However, in terms of feasibility, it is just as necessary to neglect certain aspects that have little impact on the overall result. In the practice LCA, there are therefore recognised cut-off criteria for deciding which inputs (e.g. mass, energy, and environmental relevance) to include in the assessment.[113,114]

A number of influencing factors can be disregarded for the present comparative ecological assessment of the packaging variants analysed because it can be assumed that these have only a minor influence on the result. The influencing factors to be neglected are determined using the cut-off criteria. These define the quantity of an energy flow or the degree

[112] Cf. Bulach et al. (2022).

[113] "In life cycle assessment, cut-off criteria are defined as the amount of material, an energy flow, or the degree of environmental relevance associated with process modules or product systems that are to be excluded from a study". – DIN EN ISO 14040:2006.

[114] Cf. DIN EN ISO 14044:2018-05.

of environmental relevance in connection with process modules or product systems that are to be excluded from a study.[115,116] The cut-off criteria used and the assumptions on which they are based are briefly explained below:

- **Dimensions:** When using mass as a criterion, all inputs that cumulatively contribute more than 5% to the mass input of the product system to be modelled must be included in the study.
- **Energy:** The use of energy as a criterion also requires the inclusion of all inputs in the study that cumulatively contribute more than 5% to the energy input of the product system.
- **Environmental relevance:** Environmental relevance serves as a criterion insofar as all inputs that cumulatively contribute more than 5% to the overall result of the impact indicators of the product system analysed must be included in the study. The data quality requirements with regard to mass are met in this study (i.e. all inputs recorded in the course of data collection are included in the balance if they together account for more than 5% of the total mass input). The life cycle inventory data for the provision of PP recyclates from LWP waste is analysed in this report using the data collected in Bulach et al. (2022).

The data quality of this study fulfils the aforementioned requirements. The criterion relating to the balanced consumption of materials and energy is met for production at the Jokey plant because the balance is based on the consumption measured in production or verified in the corresponding invoices (electricity bill, gas bill).

[115] Cf. DIN EN ISO 14040:2006.

[116] Cf. DIN EN ISO 14044:2018-05.

3.3 Stocktaking of the life cycle inventory

3.3.1 Data for the ecological assessment

As part of the inventory, data on ecologically and economically relevant aspects in the following three areas of application were collected. The ecological comparative calculation takes into account all three of the areas of application outlined below for the product variants under consideration along their entire life cycle.

Location-based perspective ("gate")

At this level, the focus of the life cycle approach is on the evaluation of materials and manufacturing processes – in particular to assess the energy and resource consumption of product manufacturing.

Table 4 and

The stocktaking of the life cycle inventory for the recovery of recyclates from the mechanical recycling of LWP waste is based on parameters provided by Cyclos HTP.

Table 5 show the foreground data on relevant input and output parameters collected from the case study of the injection moulding process at Jokey SE in aggregated form. All quantities are related to the functional unit (cf. Chapter 3.2.2).

Table 4: Life cycle inventory of the inputs into the manufacturing process

Inputs	Paint bucket made from primary plastic	Paint bucket made from recycled plastic
Raw materials/pre-products	Quantity in kg	Quantity in kg
PP pellets	0.4 (virgin material)	0.374 (recyclate) 0.020 (virgin material)
Colour pigments	0.008	0.0083
Other additives	0.00031	0.00030
In-mould label bucket	0.01	0.011
Lid	0.096	0.102
In-mould label lid	0.0025	0.0025
Auxiliaries and materials	Quantity in kg	Quantity in kg
Refrigerants	0.000000284 0.0000000126	0.000000291 0.0000000129
Tap water	0.049	0.050
Lubricating oil	0.00252	0.00258
Packaging material 1 Grey paper	0.000216	0.000216
Packaging material 2 LDPE film	0.00211	0.0021
Packaging material 3 Euro pallet	0.064	0.064
Packaging material 4 Adhesive tape	0.0000657	0.0000657
Packaging material 5 Cardboard	0.000576	0.000576
Energy source	Quantity in kWh	Quantity in kWh
Electricity	0.337	0.344
Thermal energy	0.0137	0.0135
Transport	Distance in km	Distance in km
Lorry (25 t total weight)	300	300

The stocktaking of the life cycle inventory for the recovery of recyclates from the mechanical recycling of LWP waste is based on parameters provided by Cyclos HTP.[117]

[117] Cf. Institut Cyclos HTP GmbH (2022).

Table 5: Life cycle inventory of the outputs from the manufacturing process

Inputs	Paint bucket made from primary plastic*	Paint bucket made from recycled plastic*
Waste	Quantity in kg	Quantity in kg
PP losses (e.g. off-cuts/rejects)	0.000213	0.000218
Packaging waste	None	None
Commercial waste	0	0
Waste oil/grease waste	0.00252	0.00258
Waste water	Quantity in kg	Quantity in kg
Waste water	0	0

The specific output-related energy consumption for the production of the PP fraction analysed here can be estimated only as a rough approximation at best:

- Specific energy consumption of LWP sorting: approx. 50 kWh/t input

The energy consumption of rPP regranulate production is highly process-dependent. In the course of this study, an average energy demand (electricity) of 1.2 kWh/kg rPP and a water consumption of 0.7 l/kg rPP were calculated. In addition, the recycling of 0.26 kg of recycling waste (thermal recycling) is also included in the life cycle assessment. The yields of the LWP sorting and PP recycling are listed below:

- Yield of LWP sorting: 49% PP LWP in relation to the input
- Yield of recycling: 70–74% PP recyclate in relation to the input

Upstream chain perspective (towards the "cradle")

The focus here is on the evaluation and supply chains of all preliminary products procured by suppliers and, in particular, on determining the "ecological rucksacks" of the materials and energy used. This applies in particular to the consideration of products containing recycled materials.

It can be assumed that the life cycle of packaging made from recycled materials does not begin with the extraction of recycled plastics from LWP waste but rather with the extraction and processing of the primary raw materials (crude oil) into primary plastics. Plastics that make up the recycled LWP (not known in detail) were mapped in the Life Cycle Inventory using entries from the Ecoinvent database.

A generic allocation rule was applied (cf. Chapter 3.2.4). Furthermore, the environmental impact of waste sorting and the recycling processes of plastic waste for the production of plastic recyclate are taken into account.

Downstream chain perspective ("gate to grave")

These aspects include the distribution and filling of the use phase of the paint buckets, the utilisation phase, and the processes at the end of the life cycle (e.g. renewed recycling, waste incineration). Because the two product variants do not differ in terms of their usage properties, they are, in principle, subject to the same application processes in practice.

The paint bucket made predominantly from recycled plastic thus has almost the same mechanical properties and product life as the paint bucket made from virgin plastic. There is thus no difference in terms of the stackability of the containers on Euro pallets and, as a result, transport by lorry.

Also with regard to the thermal recycling of the paint buckets at the end of their life cycle (end-of-life), the same calorific value is assumed in both variants as a substitute fuel in cement production. Because both product variants have almost identical properties from a downstream perspective, these aspects will not be described in detail here.

3.3.2 Data for the economical assessment

When analysing the costs of the LWP sorting and recycling process, around 70% of the treatment costs can be attributed to general processes such as transport, pressing, dust extraction, steel construction, and fire protection.

- Sorting costs (treatment costs): approx. 80 EUR/t input
- Revenues for recyclate: Daily price[118].

[118] The prices used to linked to the virgin process (approx. 80% of the price of virgin material); prices for recyclates are now higher because of demand; for high qualities, prices are even many times higher (last updated: October 2022).

4 COMPARATIVE ECOLOGICAL AND ECONOMIC ASSESSMENT

4.1 Ecological assessment

4.1.1 Cumulative energy demand

At first glance, the interpretation of the results for the cumulative energy demand (CED) is quite extensive and complex. Some background information is therefore required. However, it is immediately apparent that the virgin material bucket has a considerably higher cumulative energy demand than the recycled bucket. The negative values for both bucket variants are primarily due to the credits (electricity and heat) in the end-of-life phase (cf. **Figure 9**).

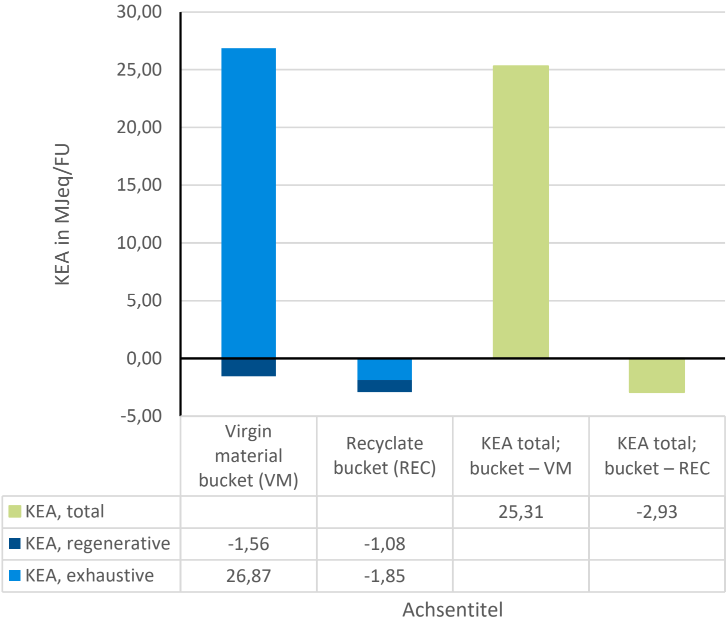


Figure 9: Cumulative energy demand per functional unit

In **Figure 9**, the individual values of the $CED_{regenerative}$ (in dark blue) and $CED_{exhaustive}$ (in medium blue) are shown separately for both variants on the left. On the right, the total net bar CED (in green) is shown for the virgin and recyclate variants. As mentioned above, the total CED of the recyclate bucket is negative (i.e. more energy is recovered during the thermal recycling of the PP than is required for the recycling process and for the production of the bucket).

It can also be seen that the energy forms exhaustible (fossil) and renewable (biomass) are decisive for the results of both bucket designs. The primary energy consumption (MJ_{eq}) of the virgin material bucket is almost exclusively due to the production of the PP. For the recyclate variant, on the other hand, it is assumed that the material from the LWP waste is fed into the recycling system without the use of primary energy (i.e. burden free).

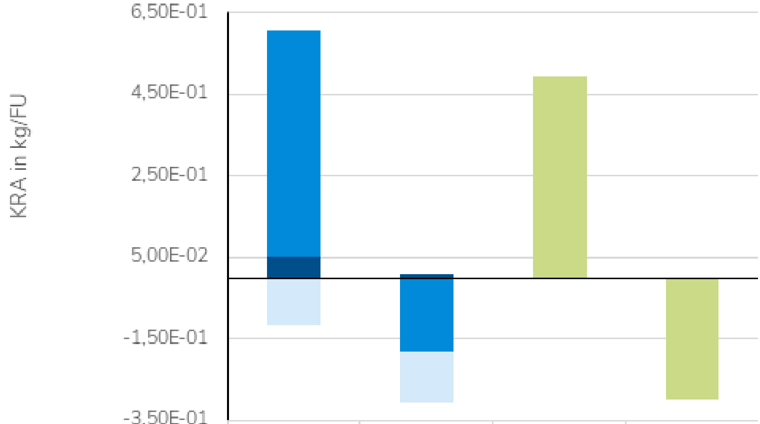
4.1.2 Accumulated raw material demand

A distinction is made between four different types of cumulative raw material demands (CRD)[119]:

- the energetic CRD
- the metallic CRD
- the biotic CRD
- the raw material demand for construction and industrial minerals.

The results for the cumulative raw material costs of the product variants analysed are shown in Figure 10. The individual CRD indicators for both bucket variants are shown separately on the left, and the net CRD “total” values for the virgin material and recyclate variants are shown on the right.

[119] **Cf. VDI 4800 - 2:2018-03.**



	Virgin material bucket (VM)	Recyclate bucket (REC)	KRA, total bucket – VM	KRA, total bucket – REC
KRA, total			4,92E-01	-2,97E-01
KRA, biotic	-1,15E-01	-1,23E-01		
KRA, energetic	5,58E-01	-1,84E-01		
KRA, construction and industrial materials	-9,13E-05	-9,67E-05		
KRA, metalic	5,03E-02	9,86E-03		

Figure 10: Cumulative raw material demand per functional unit

The $CRD_{energetic}$ clearly dominates the overall result for both bucket variants. In the case of the virgin material bucket, the raw material extraction and material production of the PP contribute 85% to the CRD. With the recycled bucket, on the other hand, it is the PP recycling and the injection moulding process, albeit with a lower overall value than with the virgin material bucket. The CRD of the recyclate bucket is negative (analogous to the CED) because the LWP waste flows into the analysed system boundary without any load (cf. Chapter 3.2.4). The recycling of the used recyclate buckets is attributed 100% to this system. The CRD_{biotic} is negative for both bucket variants. This is due to the credits (electricity and heat) in the course of the end-of-life phase.

4.1.3 Water consumption

The total water consumption for the products analysed is shown in **Figure 11.**

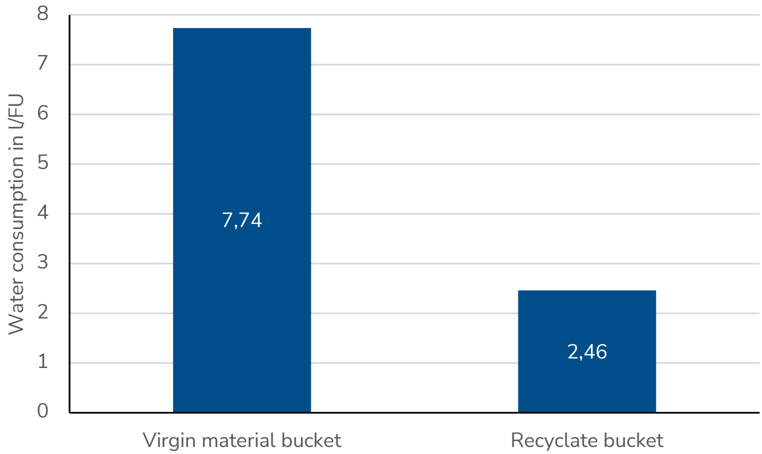


Figure 11: Water consumption per functional unit

The results show that the recycled bucket uses only around a third (approx. 2.46 l/FU) of the water compared with the virgin bucket (7.74 l/FU). Compared with other manufacturing processes (e.g. conventional and additive manufacturing technology for metals[120]), the water consumption is many times higher. Depending on the production process, consumption values of 22–145 m^3/FU are achieved.

The above comparison of the production processes for paint buckets shows that water consumption is low for both bucket variants.

[120] **Cf. VDI Zentrum Ressourceneffizienz GmbH (2019).**

4.1.4 Greenhouse gas emissions

The total global warming potential for the bucket variants analysed is shown in Figure 12.

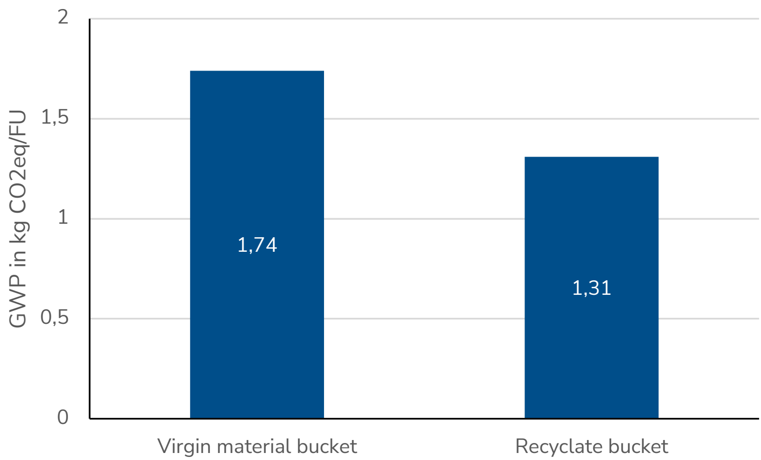


Figure 12: Global warming potential per functional unit

Figure 12 shows that the recycled bucket produces 25% less greenhouse gas emissions than the virgin material bucket. The respective life cycle stages and the percentage contribution to the overall result of both bucket variants are listed below.

In the virgin material variant, 46% of GHG emissions are attributable to raw material extraction and PP production, 43% to the end-of-life phase, and 11% to product manufacturing. The picture is different for the recyclate bucket. Here, 59% of GHG emissions are attributable to the end-of-life phase (75% thermal recycling in the cement plant and 25% in the waste incineration plant) and 18% to the manufacturing process (injection moulding). The provision of PP recyclate contributes only 23% to the total GWP (LWP collection = 2%; sorting = 3.5%; PP recycling = 17.5%).

4.1.5 Utilisation of land

In the impact category utilisation of land, the values for both bucket variants per functional unit are close to zero and therefore not relevant. However, for recycling companies and plastics processing companies, the space required for the storage and handling of raw materials as well as outgoing goods is an economically relevant aspect. Operational space requirements are a question of optimising operational processes. However, this aspect is not the subject of the impact category analysed here, which focuses on land use in the upstream chains.

4.2 Raw material criticality - supply risk

The methodology from VDI standard 4800 - 2 “Resource efficiency – Evaluation of raw material demand” is used to assess the criticality of the raw materials used. The standard is based on a system of 13 indicators categorised into three groups (cf. table 6.)

Table 6: Indicators of VDI 4800 – 2

Geological, technical, and structural indicators	Geopolitical and regulatory indicators	Economic indicators
Ratio of reserves to global annual production	Herfindahl–Hirschman index of reserves	Herfindahl–Hirschman Index of companies
Degree of co-production/subsidiary production	Herfindahl–Hirschman index of country production	Degree of increase in demand
Degree of dissemination of functional end-of-life recycling technologies	Political country risk	Technical feasibility and economic viability of substitutions in main applications
Economic viability of storage and transport	Regulatory country risk	Annualised price volatility
Degree of distribution of natural occurrences/producing areas		

Each raw material receives a rating for each indicator. The rating scale ranges from 0 to 1 and includes the intermediate steps 0.3 and 0.7. Individual raw materials are valued using a figure. The individual indicator values are sorted by size. Weighting factors G_i are calculated according to the following formula:

$$G_i = \frac{2^{(i-1)}}{3^i}$$

These are multiplied by the indicator values and added up to an overall criticality according to the following formula:

$$K_j = \frac{1}{\sum_{i-1}^{j} G_i}$$

VDI standard 4800 - 2 contains assessments based on calculations, estimates, and expert opinions for many of the raw materials under consideration. The complete table with the indicator values can be found in the aforementioned standard[121].

In the course of balancing the two bucket variants, the metals used were also analysed. Their composition and the corresponding masses in relation to the functional unit can be found in Table 7.

Because the two bucket variants are made entirely of PP, the values shown result exclusively from the processes of the respective upstream chains.

[121] Cf. VDI 4800 - 2:2018-03.

Table 7: Criticality values for metallic raw materials

Metal	Virgin material bucket (kg/FU)	Recyclate bucket (kg/FU)
Iron	6.20×10^{-4}	1.30×10^{-3}
Aluminium	1.70×10^{-4}	6.40×10^{-5}
Titanium	1.60×10^{-4}	1.79×10^{-5}
Copper	1.20×10^{-4}	-
Chromium	1.00×10^{-4}	1.97×10^{-5}
Zinc	-	1.38×10^{-5}

The criticality of natural gas and crude oil was also determined. Their masses or volumes in relation to the functional unit are listed in Table 8:

Table 8: Criticality values for fossil raw materials

Raw material	Virgin material bucket (kg or m^3/FU)	Recyclate bucket [kg or m^3/FU]
Crude oil [kg]	0.396	0.015
Natural gas [m^3]	0.820	~0

Based on the data from Table 7, it can be seen that metals are of little importance in the context of this study. The reason for this is that neither machines nor tools were taken into account in the foreground data. For the sake of completeness, the raw material criticality of the metals identified was nevertheless assessed. The standardised weighted values for both bucket variants are shown in Table 9:

Table 9: Weighted raw material criticality of the metals identified

Metal	Virgin material bucket	Recyclate bucket
Iron	0.7322	0.7322
Aluminium	0.7655	0.7655
Titanium	0.8349	0.8349
Copper	0.7259	-
Chromium	0.9282	0.9282
Zinc	-	0.9163

Because the metals identified and listed in Table 9 are small in terms of mass, the criticality of supply (except for titanium) is considered low.

The situation is different with regard to the criticality of crude oil and natural gas. Fossil raw materials are required for the production of both bucket variants. The standardised weighted values for crude oil and natural gas are shown in Table 10:

Table 10: Weighted raw material criticality for fossil raw materials

Raw material	Virgin material bucket	Recyclate bucket
Crude oil [kg]	0.688	0.688
Natural gas [m^3]	0.820	-

The indicators were last updated in 2018. However, the geopolitical situation has since changed because of the conflict in Ukraine. In particular, the supply criticality of crude oil and natural gas has increased considerably for Germany since 2022. The values determined here in accordance with the indicators of VDI standard 4800 - 2 can therefore be set considerably higher from the current perspective (as of the end of 2022).

4.3 Economic assessment

This is followed by an orientating production cost analysis (including raw materials, operating materials, energy costs) and then an economic discussion of the market environment as well as the effects of potential legislative interventions. An analysis of the life cycle costs typically presented here (analogous to the ecological comparative calculation) is obsolete with regard to the object of investigation. The reason for this is the use of high-quality recyclates, which do not require any noteworthy additional investment in processing equipment.[122] For this reason, a comparative investment cost calculation (e.g. with present value calculation, interest assumptions, discount factor) does not appear to be particularly productive. This

[122] **This applies only if no manufacturing processes for food and non-food applications have to be separated from each other in the production process.**

applies to recycled plastics (in this case recycled polypropylene pellets), which have comparable technical processing parameters to virgin material when placed on the domestic market. For example, it is possible to equip the existing machines (plasticising units in the injection moulding process in accordance with DIN 24450) with recycled PP pellets instead of primary PP pellets in the same way. The cost analysis shows that the only variable cost factor is the different purchase prices of the two raw materials in production (cf. Chapter 3.2.2). Meanwhile, all other operating costs can be assumed to be the same.

4.3.1 Relative costs

The following analysis is based on aggregated costs for the respective production steps. No detailed, absolute cost data can be published for reasons of confidentiality vis-à-vis the case study provider, Jockey. Instead, the relative cost shares are presented in an aggregated and relative form (cf.. Figure 13).

The cost analysis shows that the purchase price for raw materials (between 54 and 62% of the total specific production costs) as well as other preliminary products such as additives (between 37 and 45%) are almost exclusively responsible for the production of plastic buckets.

In contrast, other operating materials and specific energy costs per bucket play a negligible role. It can be deduced from this that purchase prices – both for primary PP pellets and secondary PP pellets – are highly elastic in relation to the overall cost structure of production. This means that relative changes in the price of raw materials in purchasing are also reflected to a considerable extent in the pricing of the end product.

The example presented here therefore shows that it is perfectly possible to produce the plastic paint bucket analysed more cost-effectively using recycled PP than with primary PP (cf. Figure 13).

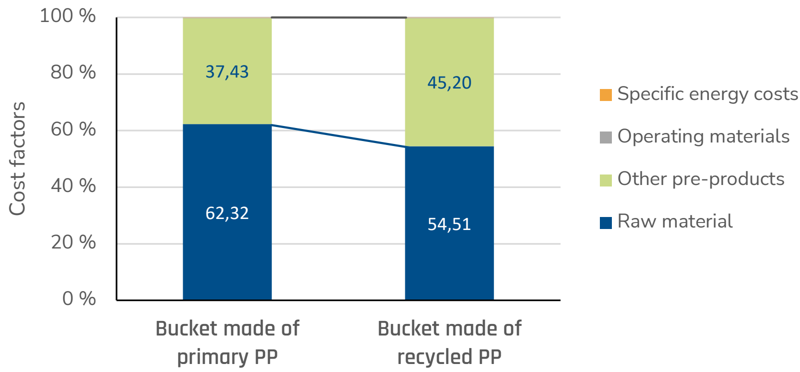


Figure 13: Comparison of relative cost shares in the production of plastic buckets from primary PP vs recycled PP[123]

4.3.2 Price trends and market environment

As shown above, the purchase price of primary and secondary plastic pellets has a considerable influence on the total production costs of the paint bucket. Because high-quality secondary PP is procured through long-term supply contracts in the case study under consideration (cf. Chapter 3.2), recyclate is the more profitable option in comparison.

[123] Own illustration based on data provided by Jokey SE for this study.

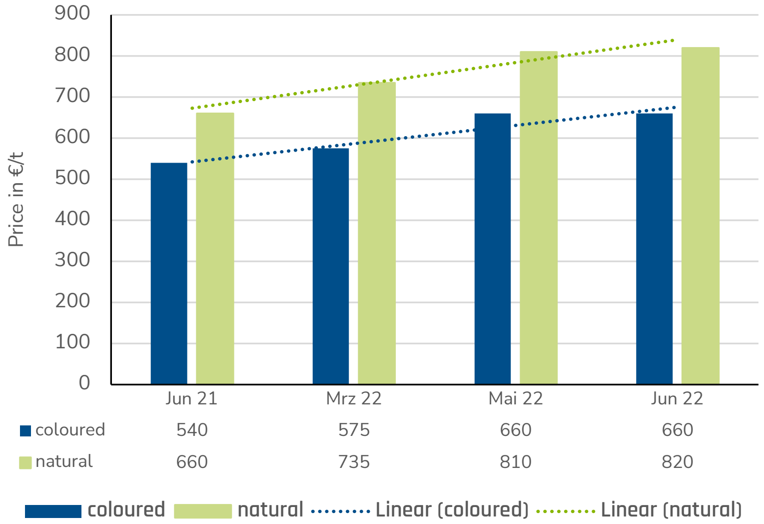


Figure 14: Price development of secondary, homopolymeric PP waste plastics in Germany[124]

However, the current market environment for high-quality PP recyclates is increasingly tense because of increasing prices. As shown in Figure 14, the relevant prices rose by 20–25% between June 2021 and June 2022 (basis: June 2021). This may be due to the considerable increase in demand for secondary plastics because of the rising cost of primary plastics as a result of current global energy policy developments and the associated increase in the price of crude as a raw material for primary plastics. It is therefore by no means clear at present that plastics processing companies can adopt this business model as a "blueprint".

4.4 Sensitivity analysis

In the ecological assessment of products with recyclate content, the allocation used is essential for the balance sheet result. This refers to the

[124] Own presentation based on Euwid, values averaged.

distribution of environmental impacts between the first life cycle of the PP in the form of lightweight packaging and the product system under consideration in which the recyclates are used. In life cycle assessment practice as well as in scientific discourse, there is still no consensus on which allocation rule should be applied. The South German Plastics Centre (SKZ) has launched a trial together with the German Federal Environmental Foundation as the funding body. As part of the research project SCO2RE – CO_2 balancing of technical plastic recyclates, a guideline with a checklist and a method report on the balancing of plastic recyclates were published in 2021. The documents can be downloaded free of charge and without registration directly from the homepage of the SKZ.[125]

The following provides a brief overview of the two scenario/sensitivity variants analysed in comparison to the base scenario (0/100).

The **50/50 scenario** specifies that the recyclates from LWP bear half of the environmental burdens (50%) from the original production of the LWP and half of the credits and environmental burdens (50%) from the final recycling after use. The resulting credits and environmental burdens of the first (original PP-LWP) and second (PP recyclate) life stages are distributed equally between the two life cycles (cf. Table 11).

The **50/100 scenario** specifies that the recyclates from LWP bear half of the environmental burdens (50%) from the original production of the LWP and all credits and environmental burdens (100%) from the final recycling after use. The resulting environmental burdens of the first life cycle stage (original PP LWP) are divided equally between the two life cycles whilst the credits and environmental burdens of the second (PP recyclate) are completely allocated to the latter. The 50/100 scenario is an extreme scenario (cf. Table 11).

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[125] **Cf. SKZ – Das Kunststoff-Zentrum (2022).**

Table 11: Structure of the scenarios according to the allocation rules

	1st life cycle: original PP LWP	2nd life cycle: PP recyclate	
Base scenario (0/100)			
Environmental impact from the production of original PP-LWP from virgin material	100%	0%	Base scenario (0/100)
Environmental burdens and credits from recycling after 2nd life cycle (EoL)	0%	100%	
50/50 scenario			
Environmental impact from the production of original PP-LWP from virgin material	50%	50%	50/50 scenario
Environmental burdens and credits from recycling after 2nd life cycle (EoL)	50%	50%	
50/100 scenario (extreme scenario)			
Environmental impact from the production of original PP-LWP from virgin material	50%	50%	50/100 scenario
Environmental burdens and credits from recycling after 2nd life cycle (EoL)	0%	100%	

The credits from recycling (EoL) result from energetic recycling

In Figure 15, the results of the sensitivity and scenario analysis for the global warming potential impact category are compared with the base scenarios.

The 50/50 scenario bucket recyclate performs almost exactly the same as the base scenario (0/100) bucket recyclate. The 50/100 scenario bucket recyclate can be described as an extreme scenario because the type of allocation is clearly to the detriment of the recyclate. The value here is at the level of the virgin material variant.

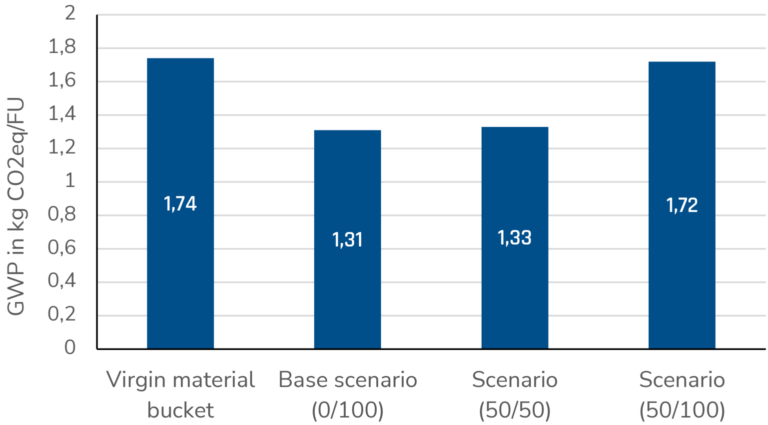
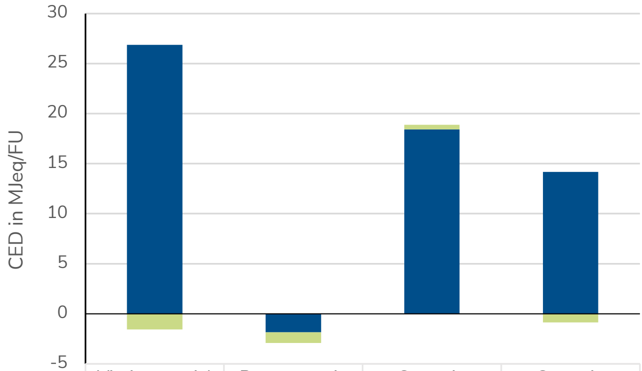


Figure 15: Comparison of the global warming potential of the scenarios

With regard to CED (cf. Figure 16), the picture is completely different compared with the impact cat-egory of global warming potential.

The 50/50 scenario bucket recyclate performs worse than the 50/100 scenario bucket recyclate. The reason for this is the credits (electricity and heat) in the course of the end-of-life phase. In the 50/100 scenario, these are to be added in full to the recycling bucket. This reduces the CED compared with the 50/50 scenario in which only 50% of the credits are allocated to the recyclate bucket.

Regardless of the allocation rule selected, the recyclate bucket performs consistently better than the virgin material bucket for all environmental impact categories analysed (CRD, CED, and GWP).



	Virgin material bucket	Base scenario (0/100)	Scenario (50/50)	Scenario (50/100)
KEA, regenerative	-1,56	-1,08	0,47	-0,87
KEA, exhaustive	26,87	-1,85	18,43	14,18

Figure 16: Comparison of CED baseline scenarios with sensitivity scenarios

Assessment of relevance and scope, taking into account the assumptions made

The use of PP recyclate offers ecological advantages over virgin PP because the environmental impact of PP production from fossil raw materials (crude oil) can be attributed to the first life cycle. In addition, the calorific value of the PP produced from fossil raw materials is achieved in the form of a credit only when the recycled product is thermally recycled. Accordingly, the lightweight disposable packaging originally produced from virgin PP contributes by definition to all material-specific contributions to the CRD, CED, and GWP whilst the credit for thermal recycling benefits the recycled product.

This definition of the 0/100 allocation rule is plausible insofar as no closed material cycle is achieved with PP-based single use LWP in contrast to single-use PET beverage bottles with a deposit. Although PP-based LWP is labelled as recyclable,[126] in practice only 55% of the plastics contained

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[126] **Labelling of LWP with the recycling code and Der Grüne Punkt.**

in LWP are mechanically recycled (as of 2019).[127] Since the beginning of 2022, the specified recycling rate[128] for plastics in LWP waste has been 63%. Mechanical recycling is usually associated with cascade utilisation (i.e. the recyclates are not used to create new packaging but rather other products). Genuine “packaging to packaging” recycling – as described in this study – has taken place only to a limited extent to date.

On the other hand, the high-quality recyclate application considered in this case study is an example of true “packaging to packaging” recycling. Although the recyclate-based paint bucket is also disposable packaging, its equivalent function enables the true substitution of disposable packaging made from virgin PP with disposable packaging made from recyclate in the end target group market. Against this background, the application of the 0/100 allocation rule in the base scenario is justified and emphasises the ecological advantage of recyclates.

The results of the sensitivity analysis make it clear that high-quality recyclates still have ecological advantages over virgin PP even with less favourable allocation rules (50/50 and 50/100). However, this statement does not apply to the cascade utilisation of recyclates (downcycling) because in such cases, there is no real recycling of the plastic. The use of lower-quality recyclates for trivial applications (e.g. park benches) leads to the substitution of other materials (e.g. wood). The results of this study do not apply to this.

Discussion of possible sources of error

The following section briefly discusses possible sources of error in the LCA results starting with the data basis. The quality of the primary and secondary data is generally quite good. A detailed description of the data quality can be found in Chapter 3.2.5. The modelled processes, including their

[127] **Cf. Umweltbundesamt (2022b).**

[128] **Cf. VerpackG (2019).**

input and output data, reflect industrial practice; this is why no significant sources of error can be found here per se. Therefore, more detailed explanations of the individual processes follow here starting with the bucket made from virgin material.

In the case of the paint bucket made from virgin PP, the actual raw material extraction/material production is the dominant process in the product system analysed for almost all impact categories considered. The material composition of the bucket, including its mass, is available as a primary data set and was specified as an exact value (no value ranges). Linking the above data with the database processes (e.g. PP production), including upstream chains, therefore does not harbour any sources of error. The data set for PP production was first published in 2014 and last amended in November 2021.

The data basis for injection moulding production is based on exact values provided by Jokey by means of a questionnaire. As with the production of the virgin material buckets, primary data were also used for the recycled buckets, and the injection moulding process was modelled. In a second step, this primary data was linked with corresponding secondary data from the ecoinvent database.

There is a certain potential for error when modelling refrigerants. The exact chemical composition was not used here. Instead, a comparable data set from the database (i.e. chlorodifluoromethane) was used. The situation is similar with the antistatic agent used. The database entry for the comparable compound alkyl benzene sulphonate was used here. The last change to the aforementioned data records was made in November 2021.

The modelling of the recycling of discarded buckets was based on empirically substantiated data from 2021[129]; however, this depicts the recycling of generic plastic packaging. In the course of the study, no primary data

[129] **Cf. Bulach et al. (2022).**

were collected for the recycling of the virgin material buckets. This applies also to the recyclate bucket. A deviation of the EoL phase of the buckets from the actually modelled processes can therefore be assumed.

The data for the preparation and production of secondary raw materials for the production of the recyclate buckets were taken from the Bulach et al. study (2022). Because the recyclate bucket consists of LWP waste, the assumptions and models used are in line with current practice. The same models were used for recycling the discarded recycled buckets as for the virgin material variant.

5 SYNOPSIS AND RECOMMENDATIONS

5.1 Assessment of the ecological and economic expediency of using recycled plastics for the production of new packaging

Based on the case study – a technically complex application for recyclates (buckets for wall paint) – the results of this study show a clear ecological advantage of PP recyclate over the use of the primary plastic. The comparative LCA calculation shows that the global warming potential of the recycled product is 25% lower than that of the bucket made from virgin PP. In the CED and CRD impact categories, the results for the recyclate bin are even negative (i.e. credits are counted towards energetic recycling in the disposal phase). The product variant made from recyclate also performs considerably better than the variant made from primary plastic in terms of water consumption over the entire life cycle. As the results of the sensitivity analysis show, this statement is also valid if an even burden distribution between the first and second life cycle is considered. Accordingly, the use of plastic recyclates is always advantageous from an ecological perspective.

Based on this realisation, companies can interpret the use of recyclates as a contribution to reducing their own resource consumption as well as to climate protection. Its use makes a major contribution to reducing the global warming potential of packaging. This comes into play if the recyclate-based packaging is functionally equivalent to packaging made from virgin material. In this case, packaging made from primary PP can be substituted; this, in turn, reduces the use of fossil raw materials such as crude oil. Further improvements in the contribution of recyclates to environmental relief can be expected by 2025 as the recycling rates for plastics across Europe rise to 50%. This increases the range of high-quality recyclates that are also suitable for complex target applications.

From an economic point of view, the use of recyclate is not yet on a par with the use of virgin material. However, the case study considered here shows that it is certainly possible to manufacture products from recyclates more economically than using primary plastics. However, the price trend for 2022 also makes it clear that this business model is not a “sure-fire success” in light of the increasing prices for recycled plastic pellets. This was due, in particular, to the low market price for virgin material resulting from the previously low oil prices. Although this competitive disadvantage of recyclates has been relativised as a result of the price trends for crude oil since 2022, the market prices for high-quality recyclates are naturally also affected by rising energy costs.

In addition to the general economic framework conditions, possible consequences of legislative interventions also play a role. However, under the changed regulatory framework conditions such as the EU Circular Economy Action Plan and the German Circular Economy Act (cf. Chapter 2.4), strong economic incentives for both the recycling of plastic and the use of recyclate can be expected. The rising demand for recyclate-based end products already shows that plastics users are increasingly willing to accept higher prices for these products. One of the reasons for this is the monetisation of the lower carbon footprint of recyclates. Many companies see the use of recyclate-based products as a way of fulfilling their climate policy obligations, which, in some cases, go beyond the statutory targets for the use of recyclates.

Further regulatory incentives in favour of using recycled plastics are conceivable and can be expected. For example, the introduction of a plastics levy is currently being promoted in Germany (cf. Chapter 2.4.4) in order to break the typical price link between primary and secondary raw materials.[130] Their revenues could be used to promote or subsidise the use of secondary plastics. This economic policy instrument could have a steering effect on the markets for primary and secondary raw materials and provide an actual incentive in the direction of circularity. For plastics processing

[130] **Last updated: May 2022.**

companies, this would make the use of recyclates much more profitable from an economic perspective.

5.2 Recommendations for SMEs to improve the practical applicability of recyclates

Plastics processing companies such as injection moulding companies that are considering the use of recyclates can draw on a wide range of existing experience. As a first step, an internal inventory is recommended in order to evaluate which of the products in the range of a company are suitable for the use of recyclate from a technical perspective. The focus here is initially on products without food contact because the latter are not yet permitted for the use of recyclate in Germany (PET is an exception here). On the other hand, outer packaging or outer components of sales packaging (e.g. handles) can certainly be considered. Forum Rezyklat offers a guide for this test step as a free download.[131]

Before deciding in favour of using recyclates, it should also be checked for which products the substitution of virgin material makes both ecological and economic sense. It is therefore particularly important to first identify options for avoiding waste; for example by optimising weight, omitting unnecessary components, or (re)orienting towards reusable systems. A guide for eco-design for packaging is available free of charge from IK Kunststoff.[132] This service also includes a series of practical examples for the application of the eco-design checklists and tools.

When using recyclates, it is also important to consider the legal requirements for the recyclability of the packaging produced from the outset. In order to ensure that the use of high-quality recyclate is compatible with the concept of a circular economy being pursued at the EU level (cf. Chapter 2.4.3), recyclate products should also be recyclable (or at least not interfere with recycling). Design for recycling is therefore relevant not only

[131] **Cf. Forum Rezyklat (2022).**

[132] **Cf. IK e.V. (2022).**

for products made from virgin material but also for those made from recycled plastics. The freely available online tool “RecyClass” as well as practical guidelines offer a wide range of assistance for companies to evaluate the compatibility of their packaging products with plastics recycling.[133] Another useful source of information is the Eurofins recyclability assessment guide.[134]

From the perspective of ecological and economic effectiveness, the recyclate qualities available should be used primarily in those areas of application in which a substitution of primary plastic results in high savings effects. The use of recyclates in products should not lead to a considerable increase in the consumption of plastics (i.e. no product should be manufactured solely for marketing reasons and no inferior recyclates that lead to a considerably shorter shelf life of the products made from them should be used). The contribution to reducing the carbon footprint of packaging shown in this study can be achieved only if the use of recyclate leads to actual savings on virgin material.

A further step involves testing the technical and functional parameters of recycled plastics; these must be fulfilled in the manufacturing process and on the product side. Specialists with many years of expertise in using recyclates in injection moulding recommend coordinating with suppliers on the specific application. When planning high-quality target applications for the first time, it is particularly important to draw on the expertise of recycling specialists regarding the possible uses and processing properties of recyclates. From this perspective, the development of stable partnerships with suppliers can be conducive to long-term business planning for the use of recyclate.

[133] **Cf. Plastics Recyclers Europe (2022).**
[134] **Cf. Eurofins (2020).**

However, against the background of the current strong increase in demand, there may be temporary supply bottlenecks for high-quality recyclates. This can cause problems for new customers, thereby making it difficult to establish long-term relationships with suppliers and necessitating the use of different suppliers. In order to cushion the resulting fluctuations in recyclate quality, it is advisable to initially use recyclate blends with 50% or 25% virgin material (RAL blends) because this allows the processing properties to be kept constant.

Of course, the use of recyclates should also be coordinated with existing customers. The aim here is to inform the end users of plastic products about the properties of recyclate-based products and to break down any prejudices against recyclates. In this context, a reference to best practice examples for high-quality products made from recyclates (as compiled by the RAL Quality Mark GZ 720 awarding organisation) can be helpful.[135]

In the long term, however, it makes sense to introduce standards for plastic recyclates in order to reduce the transaction costs of using recyclates. There is no doubt that case-by-case communication between plastics processing companies and recycling companies makes sense in the introductory phase. However, standardised recyclate qualities can help to reduce costs in a circular economy because case-by-case communication about recyclate properties is not necessary in mass production. In this context, it is recommended that the plastics processing industry works together with recycling companies in order to agree on binding quality classes for recyclates and establish standardised quality parameters within defined tolerance ranges.

The standard DIN SPEC 91446[136] mentioned in the Chapter 2.1.1 is a first step in this direction. However, the regulations formulated here refer only

[135] Cf. Gütegemeinschaft Rezyklate aus haushaltsnahen Wertstoffsammlungen e.V. (2022).
[136] Cf. DIN SPEC 91446:2021.

to the communication of recyclate properties and not to recyclate qualities. The digital product passport for plastic products presented by R-Cycle

2022 operationalises the exchange of data along the life cycle of plastic products based on an open digital standard format.[137]

[137] **Cf. Kunststoffe.de (2022).**

BIBLIOGRAPHY

Achenbach, H. (2022): Identifikation von Rezyklateinsatzpotenzialen durch Analyse allgemeiner Normen und herstellerspezifischer Anforderungen in verschiedenen Anwendungsbereichen [retrieved on: 19 July 2023], available at: https://www.skz.de/ forschung/projekt/rezy-spezi

Bendix, P.; Berg, H.; Sebestyen, J.; Ritthoff, M.; Perschel, L.; Eckert, D.; Kocina, R. and Achenbach, H. (2021): Förderung einer hochwertigen Verwertung von Kunststoffen aus Abbruchabfällen sowie der Stärkung des Rezyklateinsatzes in Bauprodukten im Sinne der europäischen Kunststoffstrategie. UBA-Texte 151/2021. Dessau-Roßlau [retrieved on: 11 July 2023], available at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021-11-23_texte_151-2021_rebaupro_0.pdf

BMK (no date): EU-Kunststoffstrategie [retrieved on: 12 May 2022], available at: https://www.bmk.gv.at/themen/klima_umwelt/kunststoffe/europ_kunststoffstrategie.html

BMUV (2020): Eckpunkte der Novellierung des Kreislaufwirtschaftsgesetzes (KrWG) [retrieved on: 1 May 2022], available at: https://www.bmuv.de/themen/wasser-ressourcen-abfall/kreislaufwirtschaft/abfallpolitik/uebersicht-kreislaufwirtschaftsgesetz/eckpunkte-der-novellierung-des-kreislaufwirtschaftsgesetzes-krwg

BMUV (2021): Kreislaufwirtschaftsgesetz. Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen [retrieved on: 1 May 2022], available at: https://www.bmuv.de/gesetz/kreislaufwirtschaftsgesetz

Bulach, W.; Dehoust, G.; Mayer, F. and Möck, A. (2022): Ökobilanz zu den Leistungen der dualen Systeme im Bereich des Verpackungsrecyclings. Öko-Institut e.V. [retrieved on: 19 July 2023], available at: https://www.oeko.de/fileadmin/oekodoc/Duale_Systeme_Oekobilanz_Endbericht.pdf

Bvse (no date): Verpackungsgesetz [retrieved on: 1 May 2022], available at: https://www.bvse.de/sachverstand-bvse-recycling/alles-was-recht-ist/wichtige-gesetze/verpackungsgesetz/778-verpackungsgesetz.html

Cirplus GmbH (no date): Recycelte Kunststoffe online beschaffen [retrieved on: 17 July 2023], available at: https://www.cirplus.com

Dehoust, G.; Möck, A.; Merz, C. und Gebhardt, P. (2016): Umweltpotenziale der getrennten Erfassung und des Recyclings von Wertstoffen im Dualen System. Bilanz der Umweltwirkungen. Öko-Institut e.V.

DiLinK (2020): Di-Link Policy Brief I: Stärkung des Kunststoffrecyclings – Lessons learned aus Recherche und Unternehmensbefragung [retrieved on: 19 July 2023], available at: https://www.di-link.de/veroeffentlichungen-1/

DIN EN ISO 14040:2006: Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen, Deutsche Norm, Beuth Verlag, Berlin.

DIN EN ISO 14044:2018-05: Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen, Deutsche Norm, Beuth Verlag, Berlin.

DIN SPEC 91446:2021: Klassifizierung von Kunststoff-Rezyklaten durch Datenqualitätslevel für die Verwendung und den (internetbasierten) Handel, Beuth Verlag, Berlin.

DR Deutsche Recycling Service GmbH (no date): EU-Verpackungsrichtlinie: Was gibt es zu beachten [retrieved on: 1 May 2022], available at: https://deutsche-recycling.de/verpackungsgesetz-beratung/

Duales System Deutschland GmbH (2017): DSD: Downloads – Spezifikationen, Stand 2014/Stand 2017 [retrieved on: 1 April 2022], available at: https://www.gruenerpunkt.de/de/download.html

Ecoinvent (2022): Swiss Centre for Life Cycle Inventories: ecoinvent 3.8, Ökobilanzdatenbank. Zurich 2022.

Endres, H.-J. and Shamsuyeva, M. (2020): Warum die Kreislaufwirtschaft bessere Standards braucht [retrieved on: 1 May 2022], available at: https://www.plastverarbeiter.de/ verarbeitungsverfahren/ kunststoff-recycling/kreislaufwirtschaft-braucht-bessere-standards-857.html

Engel Austria (no date): Digitale Lösungen im Spritzguss, [retrieved on: 1 November 2022] available at: https://www.engelglobal.com/de/ch/digitale-loesungen

Eurofins (2020): Leitfaden zur Beurteilung der Recyclingfähigkeit [retrieved on: 19.07.2023], verfügbar unter: https://www.eurofins.com/media/12154836/div-079-pm_de_leitfaden_zur_beurteilung_der_recycling-faehigkeit-_eurofins_version_20_stand_september_2020_final.pdf

EU Recycling (2020): Digitales Tool zur Vermarktung von Kunststoff-rezyklaten geht in die zweite Runde [retrieved on: 1 May 2022], available at: https://eu-recycling.com/Archive/26255

European Commission (2018): Eine europäische Strategie für Kunststoffe in der Kreislaufwirtschaft COM(2018) 28 final [retrieved on: 1 April 2022], available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN

European Commission (2020): Ein neuer Aktionsplan für die Kreislaufwirtschaft, COM(2020) 98 final [retrieved on: 1 April 2022], available at: https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0016.02/DOC_1&format=PDF

European Commission (2021): Kunststoff-Eigenmittel [retrieved on: 1 May 2022], available at: https://ec.europa.eu/info/strategy/eu-budget/long-term-eu-budget/2021-2027/revenue/own-resources/plastics-own-resource_de

EU-VerpackRL (2018): Richtlinie über Verpackungen und Verpackungsabfälle [retrieved on: 1 May 2022], available at: https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32018L0852&from=DE

EUWID (2021): VKU begrüßt geplante Umlegung der Plastiksteuer auf Hersteller [retrieved on: 1 May 2022], available at: https://www.euwid-recycling.de/news/wirtschaft/vku-begruesst-geplante-umlegung-der-plastiksteuer-auf-hersteller/

Forum Rezyklat (2022): Leitfaden Rezyklat [retrieved on: 19 July 2023] available at: https://www.forum-rezyklat.de/fileadmin/user_upload/20220506__FR_Leitfaden_Rezyklat_V.1.1.pdf

Gütegemeinschaft Rezyklate aus haushaltsnahen Wertstoffsammlungen e.V. (2022): Best Practice – Unsere Anwendungsbeispiel [sic!] [retrieved on: 19 July 2023], available at: https://ral-rezyklat.de/best-practice/

GVM (2021): Recycling-Bilanz für Verpackungen, Berichtsjahr 2020, Zusammenfassung der Ergebnisse, Gesellschaft für Verpackungsmarktforschung, Mainz [retrieved on: 1 April 2022], available at: https://gvmonline.de/files/recycling/Recycling_2020_Zusammenfassung_Ergebnisse.pdf

Hesselmann Service GmbH (2022): Die Plastik-Steuer 2022 [retrieved on: 1 May 2022], available at: https://www.verpackungsgesetz.com/themen/die-plastiksteuer-2022/

Hunkeler, D.; Lichtenvort K.; Rebitzer, G. (Ed) (2008): Environmental Life Cycle Costing, SETAC Publications, Boca Raton/London/New York.

IHK (no date): EU Green Deal: EU-Aktionsplan für die Kreislaufwirtschaft [retrieved on: 1 May 2022], available at: https://www.karlsruhe.ihk.de/fachthemen/umwelt/abfall/aktuelle-informationen/eu-green-deal-eu-aktionsplan-fuer-die-kreislaufwirtschaft-4884372

IHK (2020a): Rat beschließt EU-Plastikabgabe als Teil des neuen EU-Haushalts [retrieved on: 1 May 2022], available at: https://www.karlsruhe.ihk.de/fachthemen/umwelt/abfall/aktuelle-informationen/rat-beschliesst-eu-plastikabgabe-als-teil-des-neuen-eu-haushalts-4853486

IHK (2020b): Neues Kreislaufwirtschaftsgesetz in Kraft getreten [retrieved on: 1 May 2022], available at: https://www.karlsruhe.ihk.de/fachthemen/umwelt/abfall/neueskreislaufwirtschaftsgesetz/neues-kreislaufwirtschaftsgesetz-in-kraft-getreten-4933664

IK e.V. und AGVU (2020): Gesetzliche Mindestquoten für Rezyklate in Kunststoffverpackungen? Diskussionspapier zur aktuellen Debatte [retrieved on: 15 August 2023], verfügbar unter: https://www.agvu.de/de/gesetzliche-mindestquoten-fuer-rezyklate-in-kunststoffverpackungen-2515/

IK Industrievereinigung Kunststoffverpackungen e.V. (2022): Kreislaufwirtschaft: Einsatz von recycelten Kunststoffen in Verpackungen [retrieved on: 19 July 2023], available at: https://kunststoffverpackungen.de/wp-content/uploads/2022/05/IK-Positionspapier-Kreislauf-wirtschaft-Einsatz-von-recycelten-Kunststoffen-in-Verpackungen.pdf

Industrystock (no date): Rezyklat [retrieved on: 12 October 2022], available at: https://www.industrystock.de/de/unternehmen/Umwelttechnik/Recyclingindustrie/Kunststoffrecycling/Recyclat

Institut Cyclos HTP GmbH (2022): Email dated 11 August 2022.

IPCC (2021): Climate Change 2021: The Physical Science Basis, Cambridge University Press, United Kingdom and New York, NY, USA [retrieved on: 19 July 2023], available at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

ISCC (2022): International Sustainability and Carbon Certification (2022) ISCC About Objectives [retrieved on: 19 July 2023], available at: https://www.iscc-system.org/about/objectives/

ISO 15663-2:2001: Petroleum and natural gas industries – Life-cycle costing – Part 2: Guidance on application of methodology and calculation methods.

Jetzke, T. und Richter, S. (2020): Hochwertiges Recycling für eine Kunststoffkreislaufwirtschaft. Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB) [retrieved on: 1 April 2022], available at: https://publikationen.bibliothek.kit.edu/1000133939

Jokey SE (2022): JETO 110+ Datenblatt [retrieved on: 17 July 2023], available at: https://www.jokey.com/fileadmin/user_upload/Produktkatalog/Produkte/Anhang/JETOPLUS110_EN.pdf

Keyence (2023): Inline-/Offline-Messung [retrieved on: 14 October 2022], available at: https://www.keyence.de/ss/products/measure/measurement_library/basic/in_offline/#:~:text=Die%20Inline%2DMessung%20kann%20auch,der%20Linie%20(offline)%20erfolgen

KI Hub Kunststoffverpackungen (2023): KI-HUB Kunststoffverpackungen – nachhaltige Kreislaufwirtschaft durch Künstliche Intelligenz. [retrieved on: 11 July 2023], available on-line at: https://ki-hub-kunststoffverpackungen.de/

Knappe, F.; Reinhardt, J.; Kauertz, B; Oetjen-Dehne, R.; Buschow, N.; Ritthoff, M.; Wilts, H. and Lehmann, M. (2021): Technische Potenzialanalyse zur Steigerung des Kunststoffrecyclings und des Rezyklateinsatzes, Umweltbundesamt (Eds.) [retrieved on: 19 July 2023], available at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021-12-10_texte_92-2021_potenzialanalyse-kunststoffrecycling.pdf

Kunststoffe.de (2022): Daten sind der Schlüssel für mehr Effizienz [retrieved on: 19 July 2023], available at: https://www.kunststoffe.de/a/news/daten-sind-der-schluessel-fuer-mehr-effi-3064654

Lindner, C.; Schmitt, J. and Hein, J. (2020): Stoffstrombild Kunststoffe in Deutschland 2019 (Kurzfassung). Conversio Market & Strategy GmbH, Mainaschaff [retrieved on: 1 April 2022], available at: https://www.bkv-gmbh.de/files/bkv-neu/studien/Kurzfassung_Stoffstrombild_2019.pdf

Lindner, C.; Schmitt, J., Fischer, E. and Hein, J. (2022): Stoffstrombild Kunststoffe in Deutschland 2021 (Kurzfassung). Conversio Market & Strategy GmbH, Mainaschaff [retrieved on: 1 November 2022], available at: https://www.bvse.de/dateien2020/2-PDF/01-Nachrichten/03-Kunststoff/2022/Kurzfassung_Stoffstrombild_2021_13102022_1_.pdf

Maschinenbau-Wissen (2009): Prozessablauf beim Spritzgießen [retrieved on: 1 October 2022], available at: https://www.maschinenbau-wissen.de/skript3/werkstofftechnik/kunststoffe/389-spritzgiessen-prozess

Mederake, L.; Hinzmann, M. and Langsdorf, S. (2020): Hintergrundpapier: Plastikpolitik in Deutschland und der EU. Aktuelle Gesetze und Initiative, Ecologic Institut [retrieved on: 1 May 2022], available at: https://www.ecologic.eu/sites/default/files/publication/2021/20-08-04_Hintergrundpapier_Plastikpolitik-final.pdf

Ministerium für Klimaschutz, Umwelt, Energie und Mobilität Rheinland-Pfalz (2022): Eder: „Ein Quantensprung beim Kunststoffrecycling", Pressemitteilung vom 23.02.2022 [retrieved on: 17 July 2023], available at: https://mkuem.rlp.de/service/pressemitteilungen/detail/eder-ein-quantensprung-beim-kunststoffrecycling

NABU (2020): Der Aktionsplan Kreislaufwirtschaft der EU-Kommission [retrieved on: 1 May 2022], available at: https://www.nabu.de/imperia/md/content/nabude/konsumressourcenmuell/200416-nabu_aktionsplan_krw.pdf

PlasticBOND (2022): Nachhaltige Optimierung von Kunststoffverpackungen - Von Linearwirtschaft zu kreislauffähiger Wertschöpfung durch detailliertes Materialwissen und digitalen Services [retrieved on: 11 July 2023], available online at: https://plasticbond.de

Plastics Recyclers Europe (2018): European Certification of Plastics Recycling [retrieved on: 17 July 2023], available at: https://www.eucertplast.eu

Plastics Recyclers Europe (2022): RecyClass Online Tool [retrieved on: 17 July 2023], available at: https://recyclass.eu/recyclability/online-tool/

Plastship GmbH (no date): Ihr Industrie-Netzwerk für recycelte Kunststoffe und Kunststoffrecycling [retrieved on: 17 July 2023], available under: https://www.plastship.com/

RAL gGmbH (2019): BLAUER ENGEL DE-UZ 30a - Vergabekriterien Produkte aus Recyclingkunststoffen, Ausgabe Januar 2019, Version 8.

RAL gGmbH (2020): RAL-GZ 720, % Recycling Kunststoff [retrieved on: 1 May 2022], available at: https://www.ral-guetezeichen.de/gz-einzelansicht/?gz=gz_720 sowie https://ral-rezyklat.de/unsere-guetezeichen/

R-Cycle (2023): R-Cycle [retrieved on: 11 July 2023], available on line at: https://www.r-cycle.org/

Recycling Service GmbH (no date): Recyclingquote Deutschland – Vergleich mit anderen europäischen Ländern [retrieved on: 1 May 2022], available at: https://deutsche-recycling.de/blog/recyclingquote-deutschland-vergleich

Scheuermann, A. (2021): Großes Potenzial für Rezyklate in Kunststoffverpackungen [recyclates 1 April 2022], available at: https://www.chemietechnik.de/markt /grosses-potenzial-fuer-rezyklate-in-kunststoffverpackungen-123.html

Schmidt, I. (2022): Industrievereinigung Kunststoffverpackungen e. V., Experteninterview.

Schmitz, M.; Dengel, G. and Karsubke, H. (2022): Jokey SE, personal interview from 14 April 2022.

Secondtrade GmbH (no date): Ihr digitaler Marktplatz für Sekundär-Rohstoffe [retrieved on: 17 July 2023], available at: https://www.secondtrade.com

SKZ – Das Kunststoff-Zentrum (2021a): Kunststoffrezyklate: SKZ und Plastship starten gemeinsames Projekt [retrieved on: 19 July 2023] available at: https://recyclingportal.eu/Archive/68677

SKZ – Das Kunststoff-Zentrum (2021b): SCO2RE. CO_2-Bilanzierung von technischen Kunststoffrezyklaten [retrieved on: 13 October 2022], available at: https://www.skz.de/forschung/kreislaufwirtschaft/sco2re-co2-bilanzierung-von-technischen-kunststoffrezyklaten

SKZ – Das Kunststoff-Zentrum (2021c): Neues Inline-Messsystem vom SKZ erkennt Fremdpartikel in Kunststoffschmelzen [retrieved on: 14 October 2022], available at: https://www.skz.de/presse/neues-inline-messsystem-vom-skz-erkennt-fremdpartikel-in-kunststoffschmelzen

SKZ – Das Kunststoff-Zentrum (2022/2023): Identifikation der Rezyklateinsatzpotenziale durch Analyse allgemeiner Normen und herstellerspezifischer Anforderungen in verschiedenen Anwendungsbereichen - Rezy-Spezi (2022/2023), Förderkennzeichen 37823/01-3, gefördert durch Deutschen Bundesstiftung Umwelt (DBU) [retrieved on: 1 May 2022], available at: https://www.skz.de/forschung/projekt/rezy-spezi

Turuc, A. (2021): Perspektiven und Hemmnisse des Recyclings von Kunststoffverpackungen aus dem Leichtverpackungsabfall, Hochschule Rhein Main, Wiesbaden Rüsselsheim.

Federal Environment Agency (2018): EU-Plastikstrategie: Guter Ansatz, aber zu unkonkret [retrieved on: 1 May 2022], available at: https://www.umweltbundesamt.de/themen/eu-plastikstrategie-guter-ansatz-aber-zu-unkonkret

Federal Environment Agency (2019): TEXTE 124/2020Umweltzeichen Blauer Engel für Produkte aus Recycling-Kunststoffen Hintergrundbericht zur Überarbeitung der Vergabekriterien DE-UZ 30a.

Federal Environment Agency (2021): TEXTE 11/2021 Ermittlung der Praxis der Sortierung und Verwertung von Verpackungen im Sinne des § 21 VerpackG [retrieved on: 15 August 2023], available at: https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-01-22_texte_11-2020_oekologische_beteiligungsentgelte.pdf

Umweltbundesamt (2022a): Abfallrecht [retrieved on: 1 May 2022], available at: https://www.umweltbundesamt.de/themen/abfall-ressourcen/abfallwirtschaft/abfallrecht

Umweltbundesamt (2022b): Verpackungsabfälle [retrieved on: 1 October 2022], available at: https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/verpackungsabfaelle#verpackungen-uberall

VDI 4800-2:2018-03: Ressourceneffizienz – Bewertung des Rohstoffaufwands. VDI-Gesellschaft Energie und Umwelt (GEU), Verein Deutscher Ingenieure e.V., Beuth Verlag GmbH, Düsseldorf.

VDI Verein Deutscher Ingenieure e.V. (2021): Circular Economy für Kunststoffe neu denken [retrieved on: 19 July 2023], available at: https://www.vdi.de/fileadmin/pages/mein_vdi/redakteure/publikationen/VDI-Green-Paper-Circular-Economy-fuer-Kunststoffe-neu-denken.pdf

VDI Zentrum Ressourceneffizienz GmbH (2019): Ökologische und ökonomische Bewertung des Ressourcenaufwands – Additive Fertigungsverfahren in der industriellen Produktion, Studie, Berlin [retrieved on: 18 July 2023], available at: https://www.ressource-deutschland.de/service/publikationen/detailseite/studie-additive-fertigungsverfahren/

VDI Zentrum Ressourceneffizienz (2022): Kreislaufwirtschaft. Ziele einer Kreislaufwirtschaft [retrieved on: 19 July 2023], available at: https://www.ressource-deutschland.de/themen/kreislaufwirtschaft/

VDI Zentrum Ressourceneffizienz (2023): Ressourceneffizienz durch innovative Recyclingtechnologien und -verfahren, Kurzanalyse Nr. 33, Berlin [retrieved on: 18 July 2023], available at: https://www.ressource-deutschland.de/service/publikationen/detailseite/kurzanalyse-nr-33-ressourceneffizienz-durch-innovative-recyclingtechnologien-und-verfahren/

VerpackG (2019): Gesetz über das Inverkehrbringen, die Rücknahme und die hochwertige Verwertung von Verpackungen [retrieved on: 1 May 2022], available at: https://www.gesetze-im-internet.de/verpackg/

Werner. J. (2021): Intelligente Rezyklate – Durch KI den Rezyklateinsatz erhöhen. Kunststoff-Zentrum SKZ [retrieved on: 19 July 2023], available at: https://www.skz.de/presse/intelligente-rezyklate-durch-ki-den-rezyklateinsatz-erhoehen

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