



REUSE VS. RECYCLE

Comparison of energy and water consumption and circularity when closing the loop of single-use and reusable packaging

REUSE VS. RECYCLE

COMPARISON OF ENERGY AND WATER CONSUMPTION AND CIRCULARITY WHEN CLOSING THE LOOP OF SINGLE-USE AND REUSABLE PACKAGING

- Authors:** Lena Bersch, Jürgen Bertling, Jan Blömer
- Contact** **Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT**
Osterfelder Straße 3, 46047 Oberhausen
www.umsicht.fraunhofer.de
Contact: Juergen Bertling
juergen.bertling@umsicht.fraunhofer.de
- Client:** **Stiftung Initiative Mehrweg**
Taubenstraße 26, 10117 Berlin
Contact: Jens Oldenburg
j.oldenburg@stiftung-mehrweg.de
- Cover photo:** This is a symbolic AI generated image. Crates and cups are not usually washed together in the same cleaning facility or stacked inside each other. ©Jürgen Bertling
- Issue:** November 2025
- Available online:** publica.fraunhofer.de; DOI: 10.24406/publica-6950
- Terms of use:** CC-BY-NC-SA 4.0
- Citation:** Bersch, L.; Bertling, J.; Blömer, J.: Reuse vs. Recycle: Comparison of energy and water consumption and circularity when closing the loop of single-use and reusable packaging. Oberhausen/Sulzbach-Rosenberg. DOI: 10.24406/publica-6950
- Contributions (CRediT):** Lena Bersch (Conceptualization, Data Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing), Jürgen Bertling (Conceptualization, Data Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing, Project administration, Supervision), Jan Blömer (Conceptualization, Data Analysis, Investigation, Methodology, Writing – original draft)
- Original report:** This is an AI-generated translation of the original report, which was published in German. It has been reviewed by the authors. However, inaccuracies may occur due to the translation process. In case of doubt, please refer to the German version (DOI: 10.24406/publica-6370).

Financing, responsibility, and terms of use	3
How things could proceed after this study...	4
List of abbreviations	5
Executive Summary	6
1 Introduction	8
1.1 Background and objective of the study	8
1.2 Methodology	9
1.3 Comments on the assessment based on life cycle inventory data vs. life cycle assessment impact categories	9
1.3.1 Water consumption	9
1.3.2 Energy demand	11
1.4 Limitations of the analysis	12
1.5 Demonstrators	12
1.5.1 To-go cups	13
1.5.2 Boxes (crates, cartons, crates)	15
2 Legal requirements and standards for the manufacture, use, and cleaning of packaging with food	18
2.1 Plastic packaging	19
2.2 Packaging made from paper and cardboard	21
2.3 Specific hygiene requirements for reusable packaging	22
2.4 Conclusions regarding the depth of regulation of different types of packaging and the comparability of systems	23
3 Basics of contamination and decontamination in the circular economy	26
3.1 Contamination and cleaning of reusable plastic packaging	26
3.2 Contamination and cleaning of plastic recyclates	27
3.3 Cleaning-relevant material properties – dishwasher and recirculating resistance	29
3.4 Contamination and decontamination in paper recirculating	32
4 Comparison of the systems	35
4.1 Recirculation in the systems	35
4.2 Conversion to the same reference values	36
4.2.1 Conversion to the output of the overall system	36
4.2.2 Conversion to nominal volume as reference value	37
4.3 Recirculating of single-use plastic packaging	39
4.3.1 Generic consideration of lightweight packaging (LWP)	40
4.3.2 General considerations regarding separately collected single-use plastic waste	45
4.3.3 Single-use cups made of PP, PS, and PET	45
4.4 Recirculating of single-use packaging made from paper and cardboard	46

4.4.1	Generic consideration	46
4.4.2	Single-use cups made of cardboard	51
4.4.3	Single-use boxes made of cardboard	53
4.5	Circularity in the reusable cycle	54
4.5.1	Generic consideration of the reusable cycle	54
4.5.2	Reusable plastic cups	57
4.5.3	Reusable plastic boxes	61
5	Comparison of water and energy consumption and circularity of the two options for closing the energy and water cycle	65
5.1	Tabular overview	65
5.2	Comparison of single-use boxes made of cardboard with reusable plastic boxes	66
5.3	Comparison of single-use beverage cups made of cardboard or PP with reusable plastic beverage cups	67
5.4	Energy and water consumption taking into account the circularity achieved	68
5.5	Comparison of the study results for reusable cups and boxes	70
6	Conclusion and recommendations	72
6.1	About the study	72
6.2	The legal situation of single-use and reusable packaging	73
6.3	Contamination and decontamination in the packaging cycle	74
6.4	Processes and facilities for recirculating	76
6.5	Comparison of energy and water consumption between the systems	77
6.6	Promotion of reusable packaging	77
7	Appendix A – Glossary	79
8	Appendix B – Interview partners	79
9	Appendix C – Various calculations	80
10	Literature	82

Financing, responsibility, and terms of use

This report was commissioned by the Stiftung Initiative Mehrweg (SIM). Literature and statistical data were evaluated, and facility visits and interviews were conducted. The report represents a scientific opinion based on available data, but its interpretations are also normative in nature. No experiments or independent data collection were carried out, but some are included in the literature cited. The statements and methods in this report relate to life cycle assessments, but the report itself is not a life cycle assessment and therefore does not meet the relevant standards (e.g., ISO 14040, ISO 14067, etc.).

The authors were free to formulate the report as they saw fit; there was no influence from the client, the experts interviewed, or other third parties. Nevertheless, the client had the opportunity to critically comment on preliminary versions of the report in one round of review. The findings of the report do not necessarily represent the views of the client or the Fraunhofer Institute UMSICHT, but primarily the views of the authors involved. An internal review process took place at Fraunhofer UMSICHT.

Fraunhofer is not liable for any loss or damage incurred by third parties as a result of relying on the information contained in this report without taking into account the uncertainties of this scientific opinion.

References to this study should not refer to isolated passages of text but should be sufficiently contextualized and accompanied by a reference to the full report. The work is protected by copyright in its entirety. It is also available under a Creative Commons license (CC-BY-NC-SA 4.0 DE; for the download link and citation format, see the bibliographic data on page I of this report). The work or parts thereof may be reproduced, distributed, and made publicly available for non-commercial purposes, provided that reference is made to the authors (authors, publishers). In the event of distribution, the same license terms under which this work falls shall apply. Any commercial use without the written permission of the authors is prohibited.

How things could proceed after this study...

This study evaluates the energy and water consumption as well as the circularity achieved by single-use and reusable packaging based on literature data, statistics, and interviews. As a Fraunhofer Institute with proven experience in the ecological, economic, and technical evaluation of processes, products, and services, we see ourselves not only as neutral evaluators, but also as bridge builders between technology development, evaluation, and implementation. Our analyses are closely embedded in the technical expertise of Fraunhofer UMSICHT and thus contribute to a formative evaluation – in other words, we not only review and evaluate retrospectively, but also identify design options at an early stage, which we can then help to implement in subsequent projects.

In the context of reuse and recirculating – the topic of this study – Fraunhofer UMSICHT is researching new technologies for water conservation and treatment, modern energy concepts for the generation and storage of renewable energies, and cross-industry solutions that take specific location issues into account. We optimize fossil-based and bio-based plastics to achieve a long service life and wash resistance in reusable applications. At the same time, we are developing improved thermochemical and mechanical recirculating processes for plastics and other complex waste mixtures. Our designers create recyclable products based on advanced studies of usage behavior. When introducing new products and technologies, we examine social acceptance, economic prospects for success, and—as in this study—aspects of ecological sustainability.

Contact for further R&D activities: Jochen Nühlen
jochen.nuehlen@umsicht.fraunhofer.de

List of abbreviations

BfR	German Federal Institute for Risk Assessment (Bundesinstitut für Risikobewertung)
BYO	Bring-your-own system
BPA	Bisphenol A
DEHP	Diethylhexyl phthalate
DIN	German Industrial Standard (Deutsche Industrienorm)
DUH	Environmental Action Germany, Deutsche Umwelthilfe e.V.
EFSA	European Food Safety Authority
EPS	Expanded polystyrene
EU	European Union
FEFCO	European Federation of Corrugated Board Manufacturers
GKV	German Association of Plastics Converters, Gesamtverband Kunststoffverarbeitende Industrie e.V.
GMP-Regulation	Commission Regulation (EU) No 2023/2006 on Good Manufacturing Practice for Materials and Articles Intended to Come into Contact with Food
(r)HDPE	(recycled) high-density polyethylene
IV	Intrinsic viscosity
SLC	small load carrier
(r)LDPE	(Recycled) low-density polyethylene
LWP	Lightweight packaging (waste fraction)
MOAH	Mineral Oil Aromatic Hydrocarbons
MOH	Mineral oil hydrocarbons
MOSH	Mineral Oil Saturated Hydrocarbons
Mt	Megaton
PC	Polycarbonate
PCR	Post-consumer recycled material
PE	Polyethylene
PES	Polyethersulfone
(r)PET	(recycled) polyethylene terephthalate
PLA	Poly lactide
(r)PP	(recycled) polypropylene
PPWR	EU Regulation 2025/40 on packaging and packaging waste
PS	Polystyrene
PSU	Polysulfone
PVC	Polyvinyl chloride
TPE	Thermoplastic elastomers

Executive Summary

- 1) The data available on the recirculating of single-use and reusable packaging in Germany is insufficient. Life cycle assessments therefore often use outdated and unspecific data. However, the transition to a circular economy requires a solid data basis. Monitoring and the availability of valid and detailed data on single-use and reusable systems are therefore necessary.
- 2) Plastics made from recycled materials are more heavily regulated than cardboard or paperboard packaging, despite considerable concerns about the suitability of wastepaper for food contact. As things stand today, secondary materials are not used to any significant extent in packaging for food contact. Reusable systems, on the other hand, are successfully established in food contact due to standardized cleaning processes and traceable life cycles.
- 3) Even with difficult goods, rinsing reusable boxes requires only about 20% of the final energy and freshwater used for boxes made from recycled cardboard. The advantage increases further for lightly soiled crates, e.g., for fruit or vegetables. Reusable cups perform better than single-use cardboard cups in terms of final energy and freshwater consumption (approx. 50%) and also better than single-use plastic cups in terms of energy consumption, even though the single-use plastic cups require less water for recirculating.
- 4) Despite the high costs of recirculating, the cycle losses of single-use solutions are significantly higher (17 to 100%), suitability for food contact is rarely achieved, higher mechanical requirements are only met with low recycled content, and even with downcycling, significant quantities are lost due to collection and sorting losses and material degradation (in the case of cups, this figure is as high as approx. 80%). In contrast, losses for reusable boxes are in the low single-digit range (below 3%). Reusable cups can achieve similarly good values in closed applications (events, etc.). In open applications (to-go catering), however, the values are currently still high (up to approx. 60%) due to insufficient market coverage.
- 5) Policy measures should aim at cross-material reusable quotas and their active enforcement. In terms of funding policy, research on reusability, durability, pooling, and efficient cleaning processes should be given greater consideration in research agendas.

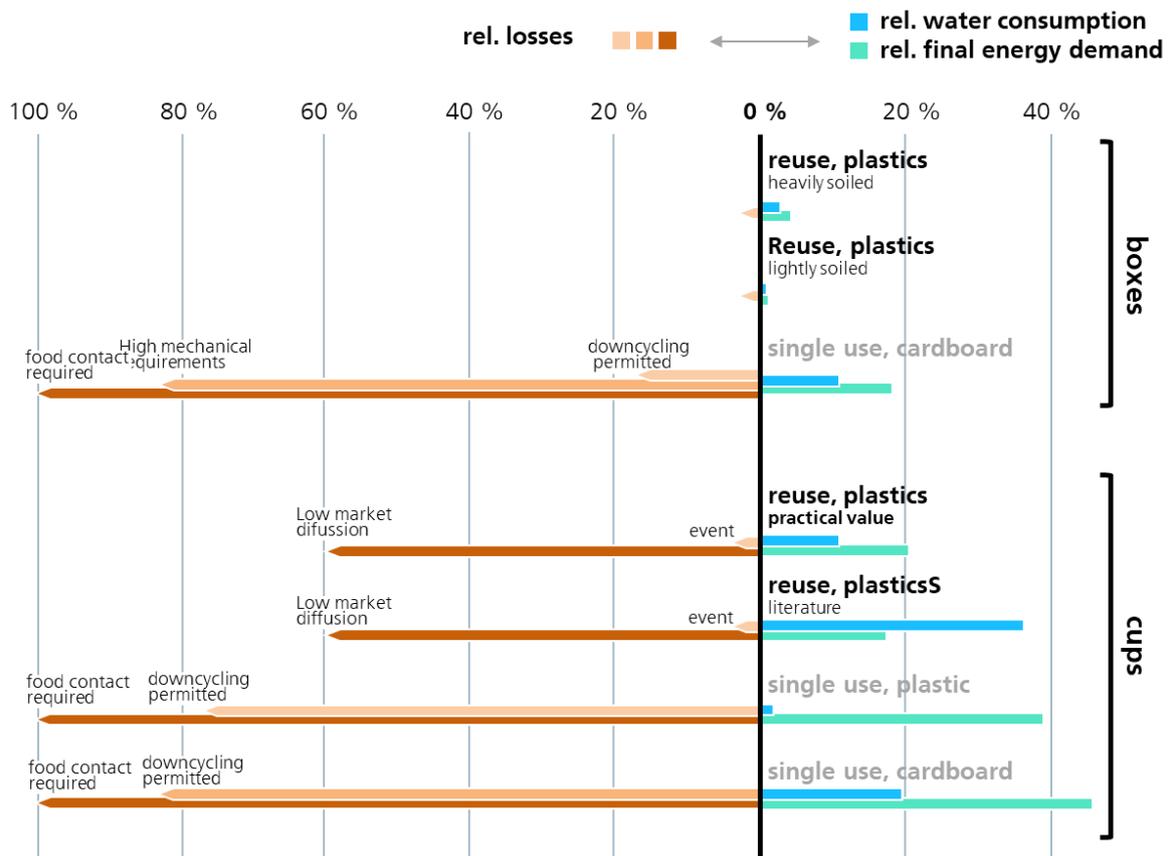


Figure 1: Presentation of the results from the comparison of different reusable and single-use systems. The upper three bar groups relate to boxes for fruit, vegetables, meat, etc., while the lower ones comprise four cups for to-go beverages. The relative consumption figures are shown on the right: **green** – final energy, **blue** – freshwater. The percentage value corresponds to the ratio to a reference value set for hand washing. On the left-hand side, the relative losses are shown as **color gradations in orange**. Relative losses correspond to the part of the material flow that is not recycled. The losses of reusable systems are weighted higher, as reusable packaging is generally more material-intensive. In the case of reusable cups, the losses vary depending on whether it is an event where return is easy or an open application with low market coverage and still insufficient return logistics. For recyclates, losses increase with quality requirements, depending on whether downcycling is an acceptable utilization option, high mechanical requirements must be met, or suitability for food contact is required. (For details and exact values, see the long version of the study).

1 Introduction

1.1 Background and objective of the study

Energy and water consumption¹, along with transport costs and specific material costs, are often at the center of the question, whether single-use or reusable packaging is the better system solution. Furthermore, this data also serves as the basis for the life cycle inventory in life cycle assessments. The aim of this report is to compile the current state of knowledge on the relevant technical processes and the associated direct energy and water consumption necessary to close the loop. Since, from an ecological and geopolitical perspective, the linear economy must give way to a circular economy in the future, and high circulation rates must therefore be achieved, the authors believe this is a sensible focus. Material production and transportation costs are not considered, as they depend on the prevalence of a system. Nevertheless, it would be useful to examine them in detail in a future study.

In the case of single-use packaging, the cycle is closed through recirculating. Recirculating comprises the process steps of shredding, sorting, washing, classifying, compounding, and molding. In reusable systems, the cycle is closed by a washing process, as long as the reusable packaging remains intact. The single-use system aims at maintaining material integrity, while the reusable system also aims at maintaining shape integrity. The simplified process of both system solutions is shown in Figure 2 below (process steps considered in this study marked in red).

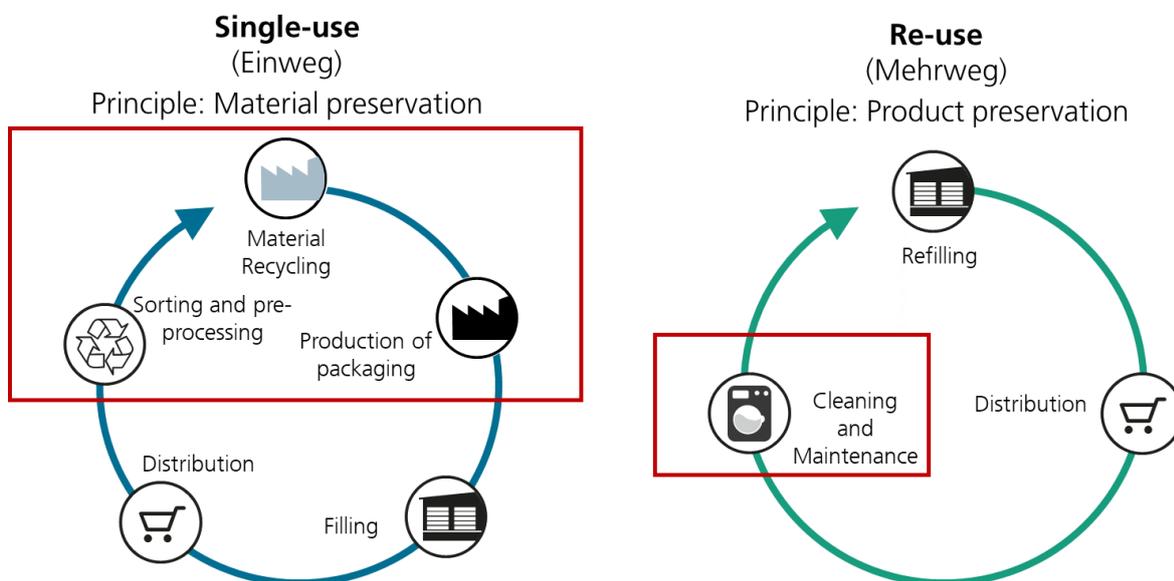


Figure 2: Simplified representation of single-use and reusable systems; study focus (direct energy, water, and auxiliary material consumption) marked in red. Transport processes are not shown [own illustration].

¹ The terms »energy consumption« and »water consumption« are not scientifically correct because they do not refer to consumption in the sense of using up, but rather to the amount used in each case. However, as the terms are established in practice, they are also used here for clarity.

1.2 Methodology

For this report, the **legal framework and current knowledge on decontamination, energy, and water consumption** in the closed-loop recirculating of single-use and multi-use systems were compiled and critically evaluated. In addition, **primary data** for reusable systems was collected through interviews and data surveys at industrial companies (see Table 17Table 1, Appendix B). No measurement campaigns were conducted. The results are presented as consumption in relation to the mass of the packaging material and the filling volumes in order to enable comparison. The circularity is assessed by calculating the water and energy consumption (see chapter 4.2) per recyclable output (secondary material or cleaned reusable packaging) and by relating it to the specific circularity or the losses of a circular option. Due to the weak and uncertain data situations and the differences in underlying system boundaries, statistical evaluations were not possible. So, instead of mean values and ranges, a justified data selection was made. Recommendations for action were derived from the analyses as part of the evaluation.

1.3 Comments on the assessment based on life cycle inventory data vs. life cycle assessment impact categories

1.3.1 Water consumption

Misunderstandings arise easily when determining and evaluating water consumption, as there are different definitions, calculation bases and methods depending on the depth of the evaluation (pure life cycle inventory or impact assessment in a life cycle assessment). An obvious approach to determining water consumption is to determine the absolute amount of water supplied to a process, i.e., the freshwater requirement. Usually a large part of this water is discharged as wastewater (except for water that remains in the product or evaporates). From a life cycle assessment perspective, the consideration of all relevant inputs and outputs corresponds to the material inventory.

Life cycle assessments analyze freshwater consumption in greater detail, taking into account various water sources and the general availability (scarcity) of water in the region under consideration. A distinction is made, for example, between surface water, groundwater, and fossil water. Figure 3 shows a schematic washing process that requires 1000 kilograms of water from a German »water mix«. 100 kg of water evaporates during the process (blue), while 900 kg are discharged as wastewater (purple). In addition, the process requires 58 kWh of electrical energy (corresponding to energy required to heat 1,000 kg of water by 50 °C). An evaluation using the AWARE model² for characterizing the environmental impacts of water use (AWARE), as also used in the calculation of product life cycle assessments according to European assessment standards (PEF 3.1)³, would in this case show a water consumption of 1372 liters, as water availability in Germany is slightly below average compared to the global average. Water discharge would amount to 1210 kg. In a life cycle assessment,

² The AWARE model (»Available WAtER REmaining«) is a characterization approach in life cycle assessment that determines how much available freshwater remains for each region after taking human and ecological needs into account, so that withdrawals can be evaluated based on their contribution to regional water scarcity.

³ PEF 3.1: Reference version of the EU »Product Environmental Footprint« method valid since July 2022 with updated characterization factors and harmonized EF database as a mandatory basis for PEF/OEF studies.

water consumption of 162 kg would therefore be included in the evaluation (difference between blue and orange bar (Figure 3)).

In addition, the procurement of electrical energy causes additional water consumption of 665 kg (light green). However, this consumption does not occur at the production site, but rather during the generation of electricity and in even earlier upstream processes (fuel supply, manufacture of PV and wind turbines, etc.). Due to the integration of background processes that cannot be influenced or can only be influenced to a limited extent, as well as the lack of regionalization of data, a life cycle assessment is only of limited use as a basis for process optimization.

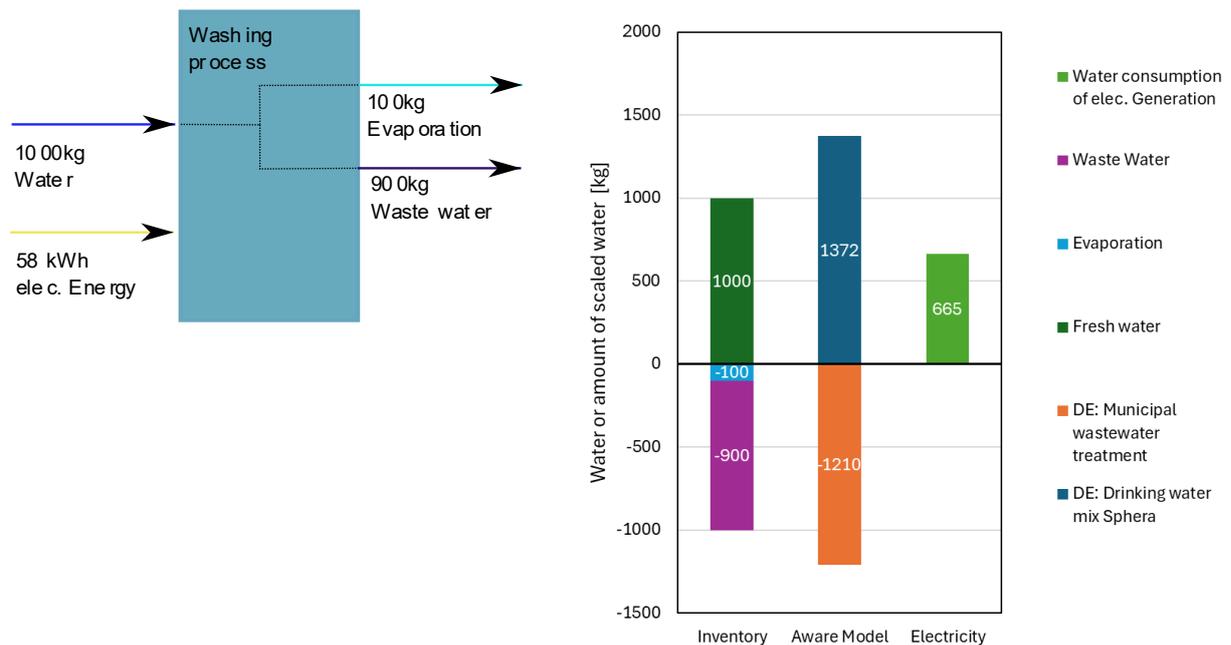


Figure 3: Schematic washing process and water consumption based on different approaches [own illustration].

From a life cycle assessment perspective, this approach to consider only the »consumed« water is understandable and correct, as its aim is to calculate environmental impacts. However, on the one hand, this contradicts the intuitive perception of water consumers, and on the other hand, it lacks an ecological incentive to use water sparingly. This appears relevant, for example, against the backdrop of the pronounced precipitation deficits in spring 2025 and the predicted increase in such dry periods⁴.

The European Federation of Corrugated Board Manufacturers (FEFCO) reports the water consumption and difference for corrugated board production (based on 1 ton of product) in a very transparent manner (total direct consumption

⁴ <https://www.umweltbundesamt.de/themen/wasser/extremereignisse/klimawandel/trockenheit-in-deutschland-fragen-antworten#trockenheit-aktuelle-situation>
<https://www.sciencemediacenter.de/angebote/fruehjahrstrockenheit-2025-in-deutschland-mit-trockenstress-in-den-sommer-25070>
<https://www.dvgw.de/der-dvgw/aktuelles/presse/presseinformationen/dvgw-presseinformation-vom-16042025-trockenheit-und-wasserversorgung>

13.55 m³, difference 1.07 m³) (FEFCO 2018) (for further details, see chapter 4.4). However, often only the water difference (water lost due to evaporation or remaining in product) is communicated. According to this logic, however, the cleaning of reusable packaging would also consume practically no water, apart from drying or evaporation losses.

For these reasons, this study uses the pure freshwater consumption of a process as the basis for its evaluation. Figure 4 shows the relationships and differences in the approach again schematically.

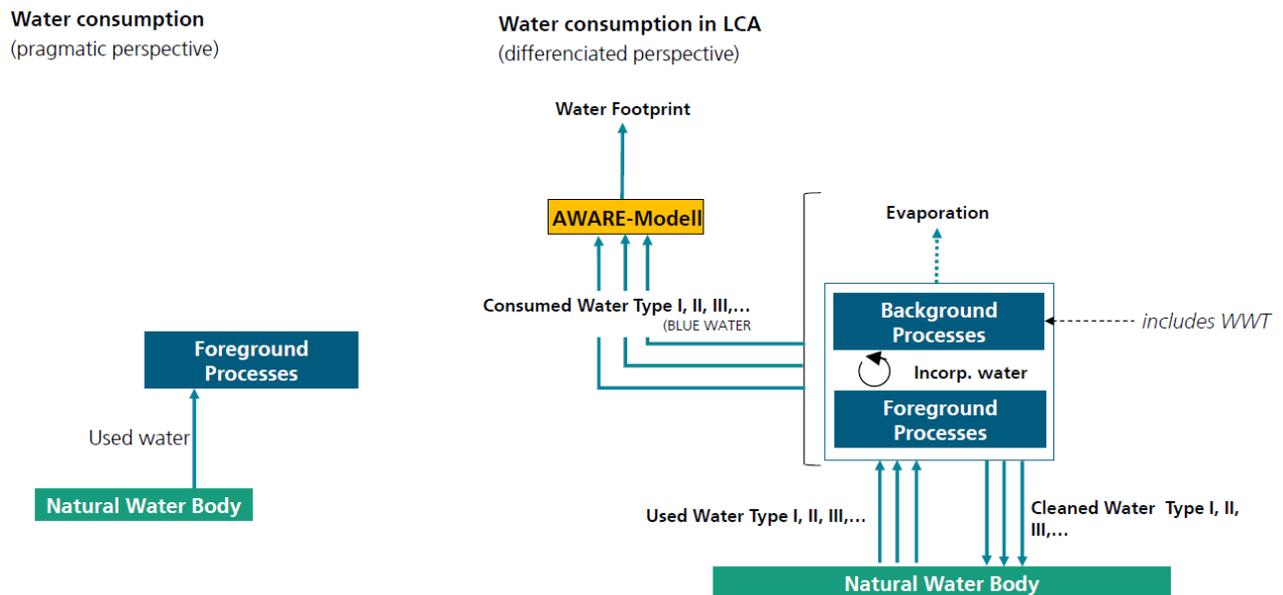


Figure 4: Freshwater consumption vs. life cycle assessment approach of water consumption [own illustration].

1.3.2 Energy demand

Misunderstandings can also easily arise when determining and evaluating energy demand, as different system boundaries and key figures are used depending on the methodology. Life cycle assessments do not usually take into account the final energy demand, but also the upstream supply chain including the raw material extraction. For this purpose, the primary energy demand or the cumulative energy consumption is used, which, in addition to the final energy actually consumed, also reflects the conversion and transmission losses in the energy systems.

However, when assessing the recirculation of packaging, it makes sense to first determine the energy directly supplied to the process – i.e., the final energy demand – and use this as a reference point. From a life cycle assessment perspective, this corresponds to the actual measured amount of energy used, e.g., in the form of electricity or natural gas, in a recycling or cleaning plant.

From a life cycle assessment perspective, the use of primary energy or CEC-values provides a more differentiated picture, as it also takes into account upstream conversion losses (e.g., in power plants or gas processing) and manufacturing costs for the infrastructure. However, these burdens do not arise at the location where the packaging is used, but in upstream energy systems. This

means that, as with water, they are only of limited use in evaluating location-specific issues or process optimizations. Focusing on primary energy requirements or on the direct incentive to reduce energy consumption during operation dilutes the issue: for the user, the decisive influencing factor is the directly purchased electricity or gas consumption, as this is directly relevant both economically (costs) and ecologically (direct emissions and resource consumption).

Another point concerns the **consolidation of electricity and gas requirements** into a single final energy quantity. Although energy sources differ in terms of their provision and use, gas consumption is relatively low, at least in washing processes and plastics recirculating, and is less significant than electricity requirements. At the same time, the electrification of production and cleaning processes is continuing to advance, meaning that in future an even greater proportion of energy will be provided in form of electricity. The carbon footprints of electricity and gas are also converging in Germany (electricity (2024): 350 g_{CO_{2e}}/kWh, gas (2024): extraction: 72 g_{CO_{2e}}/kWh, combustion 201 g_{CO_{2e}}/kWh⁵). In some European countries, the footprint of electricity is already significantly lower than that of gas (e.g., Norway, Sweden, France). The energy required for evaporation and drying processes can be drastically reduced through energy recovery using heat pumps or vapor compressors. Combining both energy sources into a final energy requirement thus facilitates comparability and focuses the analysis on the essential variable. **For these reasons, this study uses the final energy consumption of a process for its evaluation.**

1.4 Limitations of the analysis

This report aims to contribute to an informed discussion by examining in detail the most important process steps for closing the loop in terms of their water and energy consumption and the achievable circularity. The specifics, advantages, and disadvantages of these processes are thus made clear. Nevertheless, the report does **not** represent **a comparative life cycle assessment** and is therefore not suitable for making general statements about the advantages of single-use or reusable systems, nor for finding the best ecological solution at the level of a specific packaging task. For such purposes, complete life cycle assessments are required that a) map further steps in the life cycle, such as manufacturing and transport costs or the specific use of materials, b) and relate to a suitable functional unit.

1.5 Demonstrators

The client, the Stiftung Initiative Mehrweg, supported by European representatives of the reusable supply chains, selected two demonstrators in consultation with the authors, based on which the analyses were carried out. These are:⁶

- To-go cups (referred to as »**cups**«)
- Crates and boxes for fruit, vegetables, baked goods, meat, fish, etc. (referred to as »**boxes**«)

⁵ <https://www.umweltbundesamt.de/themen/co2-emissionen-pro-kilowattstunde-strom-2024>
<https://projektraeger.dlr.de/sites/default/files/2024-01/documents/WPKS-Studie-CO2-Bilanz.pdf>

⁶ The terms in bold are used as abbreviations in the following.

1.5.1 To-go cups

In this study, the to-go cup (Figure 5) represents a wide range of packaging that enables ready-made drinks and food (**takeaway food**) to be taken away or consumed on the go. The corresponding packaging systems play a central role for large events, fast-food restaurants, bakeries, and companies in the system catering industry with counter service, for online and pick-up services, and for drive-ins. Many business models would be inconceivable without them.

The Society for Packaging Market Research determined an **annual consumption volume of 281,186 tons** of »single-use tableware and packaging for immediate consumption« for Germany in 2017 (Gesellschaft für Verpackungsmarktforschung mbH (GVM) 2018). This corresponds to approximately 3.4 kg per person per year. Since 1994, this amount has been increasing by an average of 2.5% per year. The proportion of plastic in single-use tableware and packaging for immediate consumption is approximately 27.6% and has risen at an above-average rate of 3.9% per year since 1994.



Figure 5: Examples for single and multi-use cups used as demonstrators in this study.

Single-use cups

Single-use cups have become established primarily in fast-food restaurants, bakeries, chain restaurants with counter sales, online orders, and drive-ins, but also in companies: around 17% of Germans consume coffee to go at least several times a week. Their filling volume typically ranges from 80 to 600 ml. Cups, lids, and sleeves are often made of separate components. The dominant materials are **cardboard cups with polyethylene (PE) or polylactide (PLA) coating. Polystyrene (PS)** dominates among plastic cups. There are also cups made of expanded PS (EPS), polypropylene (PP), polyethylene (PET), or polylactic acid (PLA). Depending on size and design (single or double-walled), the mass

varies between approx. **4.1 and 18.2 g per cup**; the plastic content of cardboard cups is 4–7%. The single-use lid is usually made of PS and weighs about 3.2 g (Kauertz et al. 2019).

In Germany, the consumption of single-use beverage cups for hot drinks is estimated at around **2.8 billion per year** (BMUKN 2025). Of these, approximately 1.66 billion are cardboard cups and 1.14 billion are plastic cups. In the to-go sector, 1.1 to 1.2 billion cups are used. This results in a total volume of **28,000 tons per year**, 70% of which is cardboard. (Kauertz et al. 2019). No data is available for cold drinks, which are mainly served in cups at events.

The designated disposal route of single-use cups in Germany is through **dual systems (yellow bag/yellow bin)**. However, they are often incorrectly disposed of in the wastepaper collection, whereby many wastepaper sorting plants sort them out and send them for incineration (Grummt und Fabian 2023) or in the residual waste due to consumption in public spaces.

Reusable cups

Reusable cups for to-go applications are reusable drinking vessels that are either brought along by the consumers (BYO system), provided as vendor-specific cups (often with a logo), or made available in supraregional pool systems. They are returned after use, cleaned, and reused.

In 2015, Environmental Action Germany (Deutsche Umwelthilfe e.V., DUH) launched the project »Be a cup hero!« (Deutsche Umwelthilfe e.V. 2015). The first pool systems were established in Germany in 2016. Initially, many local or municipal solutions emerged (e.g., in Düsseldorf, Freiburg, Mannheim, and the district of Höxter) (Pachaly 2021). At the same time, supraregional systems such as RECUP (> 20,000 distribution points), FAIR CUP (> 30,000) and VYTAL (> 6,000) were formed. The first two systems use a deposit system (1 EUR); Vytal operates digitally without a deposit. Other models (e.g., ÖkoCup) rely on purchase cups or lower deposits of around 0.50 EUR. Return machines and guidelines (Lebensmittelverband Deutschland 2020) support hygienic returns. Reusable cups cover the **same areas of application as single-use cups**: takeaway in restaurants, bakeries, cafés, delivery services, or canteens. The aim is to directly replace single-use cups and enable convenient use through a large number of return points. **Polypropylene (PP)** currently dominates the reusable cup market. Polylactide (PLA) or styrene-acrylonitrile copolymers are sometimes used; lids and closures can be made of TPE or PP. Early municipal systems sometimes still used polystyrene solutions.

Assuming that single-use systems are used only once, and that approximately 15 million reusable cups have been issued to date, which are used an average of six times per year (Pachaly 2021), the current **usage share** for reusable systems can be **estimated at approximately 3.1%** (see Table 1). Reusable systems are currently experiencing significant growth rates in terms of the number of distribution points, cups issued and total uses. It can therefore be expected that the share of uses will continue to increase in the coming years.

Table 1: Comparison and prevalence of single-use and multiuse cup systems (Kauertz et al. 2019).

System	Material	Usage	Share of total uses [%]
Single-use cups	PS	1 140 000 000	39.4
	Cardboard+PE	1 660 000 000	57.4
Reusable cups	Plastic	90 000 000	3.1

Reusable cups are cleaned after returning and put back into circulation (reuse). Recirculating only takes place when they are damaged or no longer functional – usually material recirculating, provided that mono materials (e.g., PP) are used. Deposit or digital return systems, reverse vending machines, and clear hygiene requirements ensure high return rates and a closed loop.

1.5.2 Boxes (crates, cartons, crates)

Boxes (crates, cartons) are used for the transport of **loose but also packaged fresh produce** from the food segments fruit and vegetables, meat, fish, and baked goods. These are traditionally made of wood, cardboard, and – since the early 1990s – plastic. The boxes are classified as small load carriers (SLC) in standards. The crates are filled at the producer's premises, usually stacked on pallets, secured for transport, if necessary (e.g., with edge protection, stretch film, or transport straps), and transported through the various stages of trade to the retail sector. In addition, the contents are treated in ripening rooms, if necessary, before the goods are delivered to the retail sector.

Single-use boxes made of cardboard

Single-use boxes made of (corrugated) cardboard are used once. After filling in and transport from the harvest or packing site via distribution centers to the retail trade they are disposed of or sent for wastepaper recirculating. Initially, wood was the main material used for single-use boxes. However, cardboard boxes have dominated the fruit and vegetable sector for decades and have been further professionalized with increasing logistics standardization. Today, cardboard boxes made of **standard solid board or corrugated cardboard** are common. Since most tasks in the B2B sector involve high mechanical stress, **high-quality cardboard made of kraftliner and semi-cellulose** is established here. The cartons are often printed. Polymeric coatings are not the norm in this application but are increasingly required for hygienic reasons. The variety of materials is limited, but there are still large variations in dimensions and filling volumes.

At the end of life, commercially used cardboard packaging mainly ends up in the commercial wastepaper stream. The **material return rate** for cardboard crates is already high at **around 88%** (FEFCO 2024). This rate can hardly be in-

created any further, as the maximum number of times paper fibers can be recycled is limited by quality losses, i.e. that fresh fibers must be added constantly, even if more waste paper would be available.^{7,8}

Reusable plastic boxes

Reusable plastic crates (boxes) are stackable, sometimes collapsible small load carriers (SLC) for fruit, vegetables, meat, or baked goods. They are cleaned, inspected, and reused after return and are organized in standardized pool systems. Since the early 1990s, reusable plastic crates have been available on the market in large quantities (Euro Pool System 2021). Standardization was followed by additional sizes, collapsible versions (volume reduction of 67–87%), and the integration of codes (barcodes, GRAI, RFID) for automated tracking. Today, a **rental model** dominates, in which users pay a rental fee either per day or per cycle and return the crates after use. To date, the main area of application has been the B2B logistics chain for fresh food (fruit/vegetables, meat, baked goods). The crates are filled at the producer's premises, stacked on pallets, secured, and transported through the various stages of trade to the retail sector; if necessary, a ripening treatment is carried out before delivery to the market.

PP and HDPE are the main monomaterials used for the crates, which makes them very easy to recycle mechanically. Depending on their size, they weigh between 550 and 2,070 g; filling volumes range from approx. 9.25 to 47.14 L for the crates commonly used in the fruit and vegetable segment. There are also so-called big boxes with filling volumes of up to one cubic meter or more.



Figure 6: Various boxes and their materials as demonstrators in this study

The stock and circulation have grown significantly: in 2006, there were around 200 million reusable crates in circulation in **Europe, and by 2017 this figure had risen to around 600 million** (Behrens et al. 2018). The two largest pool

⁷ <https://www.umweltbundesamt.de/papier-pappe-kartonage-ppk-0#hinweise-zum-recirculating> (accessed on 16.9.2025)

⁸ <https://www.holbox.de/uber-uns/nachrichten/maerchen-nur-recycltes-papier-ist-nachhaltig> (accessed on September 16, 2025)

operators on the European market alone achieve a total of around 2.5 billion uses per year (Bertling et al. 2022). Number of circulations of between 30 and 150 per crate and a service life of 5 to 15 years are assumed, although our own research suggests that a **at least 100 circulations** with an approximate **rotation rate of 8 per year** is realistic (Bertling et al. 2022).

Empty crates are collected from retailers, transported to washing and hygiene centers, cleaned and dried, disinfected, if necessary, quality-checked, and then redistributed. Defective crates are repaired or discarded and usually recycled. **Return rates of over 99%** are common.

2 Legal requirements and standards for the manufacture, use, and cleaning of packaging with food

Packaging with food is subject to **strict requirements**.⁹ This applies to both single-use packaging – especially if it is made from recycled materials – and reusable packaging before reuse, whereby various hygiene regulations must be observed during cleaning, filling, and handover to the customer. The demonstrators considered here are food packaging made of plastic, paper, cardboard, carton or wood. The following section therefore summarizes and evaluates the applicable regulations and standards for single-use and reusable packaging made of the materials in question. Figure 8 at the end of the chapter provides an overview of the instruments examined.

There are **different types of regulations**, ranging from European Union (EU) regulations and EU framework directives, which are transposed into national law, to DIN standards, industry guidelines and recommendations, e.g. from the German Federal Institute for Risk Assessment (Bundesinstitut für Risikobewertung, BfR). These regulations **vary greatly in terms of their binding nature and control function** for the companies concerned. While laws and regulations represent a direct obligation for companies, voluntary commitments or statements are significantly less binding. For example, failure to comply with a statement by the BfR on the use of wastepaper as a raw material for food packaging may be interpreted as negligence on the part of the company if damage occurs, but in principle such texts are not legally binding. Standards are also often de facto mandatory in practice, but legally voluntary. This classification is important when assessing the regulation of individual packaging types.

Regardless of the material and type of packaging (single-use or reusable), **EU Framework Regulation 1935/2004** applies throughout the EU to all materials that come into contact with food – and thus also to food packaging (Europäisches Parlament; Europäische Kommission 2004) and the Commission Regulation on **good manufacturing practice EU 2023/2006** («GMP Regulation») (Europäische Kommission 2006) apply throughout the EU to all materials that come into contact with food, including food packaging. The GMP Regulation 2023/2006 sets requirements for the manufacturing and cleaning process to ensure this, for example by prescribing a quality assurance system and comprehensive documentation of quality controls.

Materials that are suitable for contact then bear the symbol shown in Figure 7. Framework Regulation 1935/2004 stipulates that food packaging must be manufactured under controlled conditions, that its properties must be harmless to health and must not affect the composition, smell, or color of the food, and that all materials and primary products for this packaging must be traceable in the supply chain. According to Article 5 of **Regulation (EC) No. 1935/2004**, the European Commission reserves the right to adopt additional »individual

⁹ The BVL (Bundesamt für Verbraucherschutz und Lebensmittelsicherheit (BVL) 2025) provides an overview of laws, regulations, guidelines, and handouts on the subject of materials that come into contact with food. Documents listed there relating to materials such as ceramics, cellophane film, or active materials, as well as specifics on the import of certain substances, are taken into account in this report.

measures« (i.e., further regulations) for certain materials, e.g., plastics, cardboard, printing inks, metals, etc. (Europäisches Parlament; Europäische Kommission 2004).



Figure 7: Symbol used in the European Union for materials intended for food (in accordance with Regulation (EC) No. 1935/2004)

The new **EU Regulation 2025/40** on packaging and packaging waste (Packaging and Packaging Waste Regulation »PPWR«) is also central to packaging in general. Among other things, it sets requirements for material restrictions, recyclability, recycled content quotas, and the use of reusable packaging (Europäisches Parlament 2025). Although the PPWR applies to packaging made from all types of materials, it places a clear focus on plastic packaging¹⁰, criticized for instance by the Environmental Action Germany e.V. (Fischer 02.05.2025), as this disproportionately disadvantages plastic. Regarding restrictions on »substances of concern«, the Commission intends to present a report by the end of 2026 listing and evaluating these substances. So far, the PPWR only specifies stricter limits for concentrations of per- and polyfluoroalkyl substances (PFAS), which have been set at a total of 250 ppb (Europäisches Parlament 2025).

Indirectly relevant to packaging is also **Regulation (EC) No. 852/2004 on the hygiene of foodstuffs** (Europäisches Parlament 2004) which prescribes the hygienic and safe handling of food by food business operators. Although this regulation does not address packaging manufacturers, it does specify how food must be packaged and stored (namely in such a way that contamination is avoided). The associated **DIN 10516** standard specifies the extent to which and how food business operators must clean and disinfect equipment, rooms, and packaging, and how this must be checked in order to comply with Regulation 852/2004 (DIN 10516).

2.1 Plastic packaging

In addition to the above-mentioned key regulations EU 1935/2004 (Europäisches Parlament; Europäische Kommission 2004) and EU 2023/2006 (Europäische Kommission 2006), the Commission has made use of the option of a »single measure« provided for in EU 1935/2004 for plastic packaging and has additionally issued **Commission Regulation EU 10/2011** (Europäische Kommission 2011) specifically for plastics. There are no such regulations (as yet) for other materials discussed here, such as cardboard or wood. The central element of EU 10/2011 is a positive list of raw materials, additives, and processing

¹⁰ In terms of quantity alone, the term »plastic« is mentioned 264 times in the regulation, »paper« or »cardboard« only 30 times, and »glass« or »wood« significantly less often (Europäisches Parlament 2025).

aids that are approved for food contact. The list is updated as needed, for example when companies submit successful applications to the European Food Safety Authority (EFSA) for the approval of additional substances. Migration limits are also specified for some of the substances on this positive list. Manufacturing companies must verify these limits, for example through laboratory tests.

In order to correctly demonstrate compliance with EU 1935/2004 and EU 10/2011, industry standards have been developed, such as the measurement of overall migration (**according to DIN EN 1186**) and the specific migration of certain substances (**DIN EN 13130**) from plastic packaging into food and how the material must react when heated in a microwave or oven (**DIN EN 14233**).

In addition, recycled plastic packaging is specifically subject to **Regulation (EU) 2022/1616** (Europäische Kommission 2022), recently supplemented by **Amendment Regulation (EU) 2025/351**. This specifies the permissible source material for recirculating, i.e., collection and pre-treatment: Plastics must come from municipal waste, either separately or together with other packaging waste, but must be collected separately from residual waste and come from objects, and at least 95% must come from food packaging. In practice, this means that plastic food packaging collected via the dual system is generally suitable for reuse in the food sector. The material collected in the yellow bag or yellow bin must then be decontaminated (Article 7) and post-treated (Article 8).

The major restriction on the use of recycled materials is that Annex I to this regulation lists only two »**suitable**« **recirculating technologies** that are generally approved for obtaining recycled materials for food applications from waste. These are

- the mechanical recirculating of post-consumer polyethylene terephthalate (PET) waste, at least 95% of which comes from food applications, and
- the recirculating of plastics from the positive list of 10/2011, which originate from closed and monitored product cycles, i.e., from production waste (post industrial recycle, PIR).

For all other **novel technologies** (processes and types of plastic), operators must apply for a positive opinion of the EFSA. They can do this in accordance with Article 14 EU 2022/1616 as soon as at least four consecutive quality reports on their technology are available, i.e., after two years of operation at the earliest (Europäische Kommission 2022). In the meantime, they are allowed to produce recyclates, process them into packaging and also offer them on the market, but initially do so without explicit approval (»positive opinion«) from the EFSA and thus at their own risk, which leads to general reluctance to extend recirculating processes to material groups other than PET (Eisenträger 25.02.2025). The entire process from set up to the EFSA's opinion can take up to 7 years (GKV 2022). In its statement, the EFSA can then specify its requirements for the new recirculating process in accordance with its assessment. For example, it could also set higher minimum percentages for non-PET materials than the 95% from food applications that currently apply, but which many companies use as a guideline when developing their processes (Eisenträger

25.02.2025). Currently, more than 40 such »novel technologies« are in development (Eisenträger 25.02.2025). The publicly accessible register of all novel technologies planned in Article 24 EU 2022/1616 has not yet been implemented (Europäische Kommission 2025a), so there is no transparency here.¹¹

The **amending regulation 2025/351** does not fundamentally change the approval procedure, but renders the approval of recirculating technologies for food applications more difficult as the requirements for providing evidence, e.g., regarding the purity of the material, have been tightened (Europäische Kommission 2025b).

Due to the complexity of the regulations, the relevant associations (**GKV, BDE, bvse**) have published **joint guidelines** containing definitions, decision trees, and practical examples to facilitate the implementation of the requirements by the industry (GKV 2022). In practice, the above provisions have meant that plastic packaging made from post-consumer recycled material (PCR) has so far been almost exclusively PET.¹²

The high requirements for hygiene and food safety are somewhat conflicting to the requirements placed on plastic packaging in terms of environmental impact and circular economy. **EU Regulation 2025/40 (»PPWR«)** stipulates both a **recirculating rate** (50%) and differentiated **recycled content rates** for plastic packaging (Europäisches Parlament 2025). For food packaging made from all plastics except PET, Articles 7(1b) and (2b) stipulate a minimum proportion of 10% from 2030 and 25% from 2040, which should constitute a strong signal to the industry. However, it is questionable whether this will lead to a significant improvement in recirculating, as paragraph 5 exempts food packaging if »the amount of recycled content [...] would result in a breach of Regulation No. 1935/2004.« (Europäisches Parlament 2025). In practice, this means that recycled materials only have to be used if they comply with the necessary limits, rather than having to ensure that they do so. Additionally, Annex V PPWR **prohibits** various **types of single-use plastic packaging**, including nets, bags, and trays for fruit and vegetables weighing less than 1.5 kg, packaging for food consumed in the hospitality industry, and packaging for single portions. (Europäisches Parlament 2025).

2.2 Packaging made from paper and cardboard

EU Framework Regulation 1935/2004 enables legislators to issue specific regulations for other materials as well, including cardboard and wood, which are also considered in this study. However, no such delegated acts exist for these materials to date, and the paper processing industry assumes that this will remain the case in the foreseeable future (European Directorate for the Quality of Medicines & HealthCare (EDQM) 2021). As a result, there are a number of voluntary commitments by the industry, consisting of the **»CEPI Responsible Sourcing Guidelines«** (CEPI 2016) and the **»CEPI Industry Guideline on the**

¹¹ In future, the register will be available on the European Commission's information portal on food contact materials at: [Food and Feed Information Portal Database | FIP](#).

¹² Since January 2025, PS yogurt cups made from PCR using mechanical recirculating have been available on the market for the first time (Wacker 2024a).

Manufacture and Processing of Food Contact paper and cardboard« (CEPI 2019).

Recommendations for paper and cardboard in contact with food regarding the paper raw materials, manufacturing aids, and paper finishing agents used are also set out by **the BfR in Recommendation XXXVI** (Bundesinstitut für Risikobewertung 2023). This states that recovered fibers from paper and cardboard may generally be used provided that they meet the general requirements of Regulation 1935/2004 (Europäisches Parlament; Europäische Kommission 2004), do not exceed the limits specified in the recommendation, and the wastepaper grades have been »carefully selected«. Specifically, it states that wastepaper of type 5.01 (mixed wastepaper) according to DIN EN 643 (DIN EN 643) and paper and cardboard from mixed waste sorting and/or other multi-component collections¹³ are unsuitable for contact with food (Bundesinstitut für Risikobewertung 2023). The types of wastepaper that may or should be used in contact with food after sorting are not explicitly specified. The CEPI guidelines merely state that types that are »clearly unsuitable for contact with food« should be excluded¹⁴, without specifying which types these are.

2.3 Specific hygiene requirements for reusable packaging

The manufacture of reusable plastic packaging is subject to all the requirements regarding safety, manufacture, and the properties of raw materials set out in the above subchapters (in particular EU 1935/2004, EU 2023/2006, and 10/2011, and in the case of recycled materials, EU 2022/1616). The Working Group on Commercial Dishwashing has compiled an overview for the usage phase (Arbeitskreis Gewerbliches Spülen 2025). **EU Regulation 852/2004 on food hygiene** stipulates that containers, transport crates, etc. must be cleaned and, if necessary, disinfected after use. Annex II, Chapter X of the Regulation also states that packaging must be designed so that it can be easily cleaned and, if necessary, disinfected (Europäisches Parlament 2004). This Regulation does not specify any requirements for single-use packaging.

DIN EN 17735 on commercial dishwashers is also relevant for cleaning, provided that the packaging is cleaned centrally or locally at the point of issue. This standard specifies the hygiene requirements for commercial dishwashers, including water quality, temperature, contact time, and the treatment agents used. A contact time of 90–120 seconds at a temperature of 80–85 °C in the rinse zone is considered a guideline value¹⁵ (DIN EN 17735). These high temperatures entail high energy requirements and limit the use of thin-walled products made of materials with low heat resistance (Hesseler 07.01.2025). An additional standard, **DIN 10522**, has been developed specifically for **reusable crates and boxes**, which distinguishes between three categories depending on the contents: low-critical (e.g., fruit and vegetables), critical (e.g., bread), and very critical containers (e.g., meat) (DIN 10522). The standard distinguishes between the required cleaning results depending on the category: less critical crates only need to be visually clean, critical crates must also have a low-germ surface (aerobic mesophilic germ count, yeasts, molds), and very critical crates

¹³ I.e. all fractions except the blue bin.

¹⁴ Original quote: »In addition, reference should be made to EN 643 [categorization of wastepaper types] to exclude those grades that are clearly unsuitable for the manufacture of food contact paper and board.«

¹⁵ Lower temperatures of 40–65 °C are specified for the preceding areas of the pump pre-cleaning zone, the pre-cleaning tank, and the cleaner circulation zone.

should also be tested for other types of microorganisms and achieve a certain degree of dryness. No specific guidelines are given for the process parameters (temperature, contact time, concentration and type of cleaner, etc.), even regarding the above-mentioned categories. Instead, it states that these parameters depend heavily on the type and extent of contamination and must be designed accordingly; in some cases, cold water may be sufficient, for example. However, if thermal disinfection is planned, a temperature of 60 °C in the cleaning tank or 80 °C in the rinse tank must be reached (DIN 10522).

Inspections are carried out by the local veterinary offices and, according to operator statements, vary in terms of the type and scope of hygiene regulations to be implemented (Hesseler 07.01.2025). The washing results in washing centers are usually checked daily using microbial swab tests and, according to **DIN EN 17735**¹⁶, at least every six months in an external laboratory. The municipal food inspection authority is responsible for checking general hygiene conditions (Bertling et al. 30.01.2025).

In many reusable applications, customers bring their own cleaned containers to a distribution point (catering establishments, chain restaurants, communal catering facilities, or retail outlets) to fill them themselves or have them filled. This is legally permissible in principle, but hygiene rules must also be observed in this case. The Food Federation Germany (Lebensmittelverband Deutschland e.V.) has **published two guidelines for companies concerned** – one specifically for **to-go cups for hot drinks** (Lebensmittelverband Deutschland e.V. 2019) and one general **guideline for various types of packaging** in (Lebensmittelverband Deutschland e.V. 2020). These guidelines are based on the principle that the seller is always responsible for the safety of the food until it is packaged. The acceptance of containers brought by customers is therefore voluntary and should always be based on the seller's risk assessment. In addition, a number of tips and a checklist for practical handling are provided – for example, to use separate tools and areas for filling the containers and to touch them as little as possible (e.g., through the filling spouts of the coffee machine).

The **PPWR promotes the use of reusable packaging** by stipulating in Article 29 that 40% of all packaging types must be reusable by 2030 and as much as 70% by 2040. For packaging used for transport between different sites of the same company, a complete switch to reusable packaging is even required. However, cardboard crates are explicitly exempted (Europäisches Parlament 2025), so a shift away from plastics towards cardboard single-use packaging is to be expected. There is also a reusable packaging requirement (Article 33) for the catering industry, from which micro-entrepreneurs are exempt.

2.4 Conclusions regarding the depth of regulation of different types of packaging and the comparability of systems

Under EU law, all food packaging must be safe for human health, must not alter the properties of food, and must be manufactured under controlled conditions. For plastic packaging, especially packaging made from recycled plastic, there are a number of additional regulations that do not exist for paper and

¹⁶ Replaces the previous DIN Spec 10534, which was valid in Germany until 2023, as well as some of the standards for commercial dishwashing DIN 10510, 10511, 10512.

cardboard, although various studies indicate that substances such as mineral oil components (CVUA Stuttgart et al. 2012) and PFAS (Langberg et al. 2024; Straková et al. 2021) also migrate from paper and cardboard packaging into food to an alarming extent.

Figure 8 shows the **most important regulatory instruments** and their scope of application, ranked according to their **degree of binding force**. For **plastic** packaging, and in particular packaging that either contains recycled materials or is intended for reuse, there are **significantly more legal requirements** (instruments with a high degree of binding force) than for packaging made from paper and cardboard. The criticism of the German Association of Plastics Converters (Gesamtverband Kunststoffverarbeitende Industrie e.V., GKV) is therefore understandable that plastic packaging is subject to more detailed requirements than any other material (GKV 2022). The hurdles for the use of **plastic recyclates** are particularly high, especially since the nature of the approval process means that there is a period of legal uncertainty of up to seven years for manufacturing companies and the register for »novel technologies« decided by the EU is not yet available.

Although **greater recirculation of plastics** is politically desirable and is enshrined in the PPWR through the new instrument of recycled content quotas, it is **hampered** by the nature of the approval process and the lack of transparency. In addition, since cardboard-boxes have been exempted from the mandatory reuse quotas and – in contrast to the original draft of the PPWR from 2022 – the bans on single-use packaging only apply to plastics (Wacker 2024b), it is **more likely that there will be a shift from plastic to cardboard in the coming years rather than a significant increase in recirculation**. Currently, the use of PCR in food packaging is almost exclusively limited to PET. Under current legislation, expansion to other materials is possible, but it involves high hurdles and economic risks for companies and is therefore unlikely in the foreseeable future, at least not in widespread application.

Paper packaging for food applications may be made from recycled fibers, provided that these meet a number of quality requirements, but here too, at least for the beverage cup demonstrator, there is no closed loop. The reason for this is that used to-go cups made of coated cardboard are correctly disposed of in the yellow bag or yellow bin (UBA 2025)¹⁷, but the paper/cardboard fraction from lightweight packaging (LWP) comes from multi-component collection and is therefore unsuitable for the production of packaging with food contact, according to the BfR (Bundesinstitut für Risikobewertung 2023). Cup-to-cup recycling is only possible for misplaced items, i.e., single-use cups that are incorrectly disposed of in the wastepaper.

In summary, it can be said that a fair comparison of the systems is currently only possible to a limited extent, as true recycling (closed-loop or at least back into the food sector) is currently not legally possible for single-use packaging, neither for plastics nor for paper and cardboard.

¹⁷ In practice, these are usually disposed of in public spaces, where waste separation does not usually take place and the cups are excluded from recirculating for food applications as residual waste.

		Regulation	Content (highlights)	Scope			
↑ Degree of legal force	HIGH	Regulations (EC) 1935/2004 and 2023/2006 («GMP-regulation»)	<ul style="list-style-type: none"> ▪ Packagin must not endanger human health or change food quality ▪ Overall limiting values for migration ▪ Good manufacturing practises (Safeguard measures, etc.) 				
		Regulation (EC) No 852/2004 sowie DIN 10516	<ul style="list-style-type: none"> ▪ Hygiene of food packaging, storage rules for packaging, requirement of easy washing and disinfection for all reusable packaging 				
		Regulation (EC) No 10/2011	<ul style="list-style-type: none"> ▪ Specific migration limits ▪ Positive list of authorised monomers, starting substances, macromolecules, additives, production aids (Annex I) 				
		Commission regulation No 2022/1616 (including correction 2025/351)	<ul style="list-style-type: none"> ▪ Source material (95 % food contact material, seperately collected) ▪ suitable recycling and decontamination technologies (quality, development, registration and compliance monitoring) 				
		Regulation (EC) No 2025/40 («PPWR»)	<ul style="list-style-type: none"> ▪ Limiting values for substances of concern, specifically PFAS ▪ Design for Recycling criteria, minimum recycled content in plastic packaging, Recycling targets, targets for reusable packaging 				
		Regulation (EC) No 852/2004	<ul style="list-style-type: none"> ▪ Hygiene requirements for production and packaging of food stuff 				
MEDIUM	DIN EN 1186, 13130, 14233	<ul style="list-style-type: none"> ▪ Measurement of migration values (following EU 1935/2004 and EU 10/2011), heat resistance 					
	DIN EN 17735, DIN 10522	<ul style="list-style-type: none"> ▪ Parameters for washing process of reusable packaging ▪ Requirements for design of boxes and crates with food contact 					
	Guideline No. 36 of the BfR	<ul style="list-style-type: none"> ▪ Waste paper: appropriate sources and limiting values 					
LOW	Guidelines Food Federation Germany e.V.	<ul style="list-style-type: none"> ▪ Hygiene, filling of customer-owned reusable packaging (BYO) 					
	Guidelines for recycled materials with food contact (GKV, BDE, bvse)	<ul style="list-style-type: none"> ▪ Registration and operation of recycling plants etc. 					
	Sourcing Guidelines, Branchenrichtlinie CEPI	<ul style="list-style-type: none"> ▪ Rezyklateignung, Barriereanforderungen, Analytik 					

Legend:

	Plastic Packaging (virgin)		Plastic Packaging (recycled)		Single-use (Paper, cardboard)		Reusable Plastic Packaing
--	----------------------------	--	------------------------------	--	-------------------------------	--	---------------------------

Figure 8: Overview of regulatory instruments for packaging in contact with food and their respective scope of application

3 Basics of contamination and decontamination in the circular economy

Both reusable plastic packaging as well as plastic and paper/cardboard waste that is processed into recyclate must be free of contaminants to ensure safe reuse in food contact. The following section explains typical contaminants, the risks associated with them, and the physical, chemical, and biological processes involved in cleaning. It also discusses the conditions for hygienic cleaning, the particular challenges of cleaning plastics, and the role of material-specific properties in the feasibility and success of cleaning.

Cleaning – whether of reusable items or plastic flakes – is based on the same fundamental physical-chemical processes. An established concept for describing cleaning processes is **Siner's circle**, which identifies **four key aspects** for successful cleaning: Chemistry (cleaning agent), mechanics (e.g., spray or brush pressure), temperature, and time (duration of exposure). All four factors work together: dirt is dissolved or emulsified by suitable chemicals, mechanical action supports removal, increased temperature accelerates chemical reactions and reduces adhesion, and sufficient time ensures that the processes run their course. In addition, water acts as a carrier medium that transfers heat and removes loosened dirt particles (IHO 2024). At the microscopic level, **various processes** take place during cleaning, depending on the type of contamination: dissolution processes (water-soluble residues such as sugar or salts dissolve in water), emulsification (fats and oils are converted into finely distributed droplets by surfactants), dispersion (solid particles are suspended), and chemical reactions (strong alkali compounds dissolve adhesions and saponify fats, acids remove limescale or other salt deposits). Temperature and chemistry go hand in hand: hot water can melt fats and soften hard deposits, as well as dissolve adhesives. Mechanical forces – such as spray jets in a dishwasher or friction in a friction scrubber for plastic flakes – break the adsorption bond between dirt and the surface and remove adhering particles or biofilms.

3.1 Contamination and cleaning of reusable plastic packaging

Reusable plastic containers, especially those used for food, typically show **organic residues** (proteins, fats, carbohydrates) after use. Such contaminants primarily pose microbiological risks. They enable the growth of bacteria, mold, and yeast, which can lead to spoilage, unpleasant odors, or pathogenic germ infestation. Germs can settle and multiply, especially in hard-to-reach corners or deep scratches. If beverage or food residues remain, they can spoil and contaminate the subsequent content. Especially in the summer months, mold often forms before the containers can be cleaned. A distinction must be made between superficial mold, which can usually be removed by proper cleaning, and mold that attacks and discolors the material, rendering the packaging permanently unusable (Bertling et al. 30.01.2025). In addition, there are also foods and beverages (e.g., coffee, curry) that have a strong inherent odor, which

transfers to the plastic and thus makes it difficult to clean and reuse reusable packaging (Bertling et al. 30.01.2025).

In addition to microbial hazards, there is also the risk **of chemical contamination**, for example from **cleaning agent residues** or from **substances migrating from the plastic** itself. Some plastics contain additives, plasticizers, or free monomers that can migrate into food under unfavorable conditions. Heating – as occurs during washing – generally increases the risk of unwanted substances migrating from packaging. For example, high washing temperatures can re-release bisphenol A (BPA) from polycarbonate (PC), which is why plastics containing BPA should not be cleaned in dishwashers. Mechanical effects, e.g., from very abrasive cleaning or UV exposure, which leads to embrittlement, can contribute to the release of plastic particles (**microplastics**).

If a reusable plastic container is to be used again in contact with food, numerous hygiene requirements must be met. For crates, these are specified in DIN 10522 depending on the goods transported (fruit or vegetables, baked goods, meat, or fish). Food businesses are subject to clear hygiene requirements, which usually also include microbiological tests (swab tests«). In commercial dishwashers, temperatures and cycles are selected to ensure that germs are largely reduced. Standards such as DIN 10510/10512 and the new DIN EN 17735 define guideline values: e.g., a minimum **cleaning temperature** of **~60–65 °C and ≥80 °C in the rinse cycle** to ensure hygienic cleanliness, and a maximum of 45 °C during pre-rinsing to prevent the coagulation of protein residues. As an alternative to this thermal disinfection, slightly lower temperatures and added chemical disinfectants can also be used, especially in situations where plastic parts are heat sensitive. Enzymatic detergents could also potentially lower the necessary cleaning temperatures, but these have only been used on porcelain and glass to date, and would first have to be tested for their suitability for plastic items (Bertling et al. 30.01.2025).

It is important that all areas of the items to be washed are accessible; complex geometries or dead spaces make cleaning difficult. The selection of cleaning chemicals for plastic objects is a task of optimization. On the one hand, proteins, fats, and other food residues must be reliably removed, but on the other hand, the agents must not attack the plastic surface to avoid cracking or decoloring.

After washing, the containers must dry completely, as germs quickly form again on damp surfaces. Plastics cool down quickly due to their low heat capacity, which makes the drying process difficult. If damp plastics are stacked or packaged, the trapped moisture promotes renewed germ growth. **Complete drying** is necessary for a hygienic effect (AKGGS 2023). In practice, drying is achieved by heating the items after washing or using blow air. There are also centrifugal dryers that remove residual moisture by rapidly rotating the objects.

3.2 Contamination and cleaning of plastic recyclates

In the plastic recycling process, source material usually originate from **PCR packaging** (e.g., used PET bottles or packaging waste from dual systems) and

can contain very heterogeneous contaminants. Typical examples include **organic residues** from the contents (food or beverage residues), foreign materials such as paper (labels), **adhesives** from labels and **composite films, paint residues or printing inks, dirt** (soil, dust), and foreign plastics or **metals**. In addition to health risks, these contaminants also pose technical risks: if they remain in the material, they can reduce the quality and stability of the recycle. Adhesive and food residues can lead to discoloration or odors in the plastic during regranulation, while dirt particles or metal pieces can damage the processing machines or appear as visible defects in the product.

Plastic flakes for use in food packaging are usually **washed** at **~80 °C** during the recycling process to remove these residues. Microbial decontamination is ensured by extrusion, which heats the material to 240 °C for at least two minutes of contact time (Eisenträger 25.02.2025). Nevertheless, **chemical contaminants** can be a problem: plastic waste may have come into contact with toxic chemicals (e.g., pesticide containers or oil canisters in the wrong recirculating stream). If these substances are not completely removed, they can migrate into food during recirculating. Therefore, plastic recirculating processes that aim to make materials usable again for food contact require very effective decontamination. When the flakes are shredded, grinding dust (or fine abrasion) is produced, which is extracted at the mill and usually thermally recycled due to the contaminants still adhering to it and the lack of purity. The proportion of **microplastics** that still adheres to the flakes afterwards can partially enter the wastewater stream (Brown et al. 2023), even if fine abrasion and sludge are removed during cold and hot washing and the wastewater is purified.

When processing plastic recyclates into secondary raw materials, the focus is on removing all foreign substances that could impair the material quality or safety. The process differs from washing dishes, but is comparable in some steps (**pre-cleaning, main cleaning, rinsing**). It usually begins with sorting and rough cleaning: contaminants such as metals, glass, or non-plastics are sorted out (APR 2025; Recycling Today 2025). The plastics are then roughly shredded, which increases the surface area for subsequent washing. The main cleaning of the flakes takes place in continuously operating washing systems. First, pre-rinsing with cold or lukewarm water can take place to rinse off loose dirt and easily soluble residues. This is followed by a hot wash for high-quality cleaning. The plastic flakes (e.g., PET flakes) are intensively washed in a heated washing module, typically at **~80–90 °C**, with water, alkaline lye, and detergents (Plastic Recyclers Europe 2024). This step removes stubborn contaminants: fats, oils, and adhesives are emulsified or softened in the hot lye bath, labels detach from the flakes, and pigments or dirt particles are suspended and discharged. So-called friction scrubbers or agitators add a mechanical effect – the flakes are rubbed against each other and against screens or paddles, which scrapes off adhering dirt. The lye wash is usually followed by a multi-stage rinsing process with clear water to remove chemicals and dissolved dirt. At the end of the washing process, the plastic flakes are clean and then dried (e.g., in thermal dryers or mechanical centrifuges), as dry material is required for further processing. A special feature of recirculating is that cleaning does not end with washing.

Further cleaning effects are achieved in the subsequent **extrusion** (melt processing) stage. During melting (**typically 200–280 °C**, depending on the plastic), any remaining microorganisms are killed. Above all, however, the melt is cleaned of insoluble residues by melt filtration. Modern extruders have filters based on metal screen changers or continuous drum filters, which retain paper fibers, metal particles, wood splinters, rubber, and other foreign matter down to very small particle sizes. Typically, such filter systems can handle contamination of several percent in the input and separate particles down to the double-digit micrometer range (Kunststoffindustrie Online 2023). In addition, vacuum degassing of the melt is often carried out: under negative pressure, volatile substances (solvents, monomers, odorous substances) are removed from the melt (Gneuß 2025; Coperion 2025). This **thermal-physical cleaning step** in the extruder contributes significantly to obtaining **odorless and hygienically safe** recyclates. For example, in PET recycling processes, residual materials are removed to such an extent in the solid-state polycondensation step or by means of special extruders that the recyclate becomes suitable for food-contact. Overall, the cleaning process in recirculating is more aggressive than for reusable items – strong alkalis and high temperatures are tolerated because the formal integrity of the product does not have to be preserved (since the flakes are subsequently extruded anyway). The goal is to obtain the purest possible polymer as output. However, it is important that the conditions do not damage the material unnecessarily. In the case of PET, for example, care is taken not to keep the flakes above the glass transition temperature for too long to avoid shrinkage or premature crystallization. At the end of the recirculating process, the result is **recycled granules** that have a high degree of purity and are used for new food contact materials – often, however, in mixture with virgin material.

3.3 Cleaning-relevant material properties – dishwasher and recirculating resistance

Plastics differ significantly from materials like glass or metal when it comes to cleaning. One relevant difference concerns the **hydrophobicity** of many plastics: nonpolar polymers such as PE or PP have water-repellent surfaces, which means that aqueous cleaning fluids do not wet them as easily. **Surfactants** are therefore essential to improve water contact and remove dirt. A second problem is **susceptibility to scratching**. Many plastic surfaces are softer and scratch more easily due to mechanical abrasion – whether from cutlery (in the case of plates/boxes) or cleaning brushes. Dirt and microbes can settle more easily in these micro-scratches. Another challenge is dimensional stability under heat. Depending on their structure, plastics have a **glass transition temperature** or melting temperature above which they soften or deform, warp, or shrink. For example, thin-walled single-use PET bottles are not designed to withstand 70–80 °C in a dishwasher – they would deform and become unusable. Containers made of PS or PLA also soften at relatively low temperatures (PS \approx 90 °C, PLA \approx 60 °C) and are *not dishwasher-proof*. In addition, certain plastics can react chemically at high temperatures: a well-known example is melamine resin tableware, especially when filled with bamboo fibers – filling or rins-

ing at temperatures above 70 °C can produce formaldehyde, which can migrate into food, as experience with bamboo melamine tableware has shown. Similarly, PC can release BPA in hot lye (AKGGS 2023; Finish 2025). For application as reusable packaging in the food sector, only plastics can be used that can withstand these stresses and do not release harmful substances.

According to DIN EN 12875, a plastic item is considered **dishwasher-proof** if its appearance and usability remain unchanged even after many machine wash cycles. In tests, this is usually checked with 125 wash cycles. Figure 9 shows the graphic symbol for labeling with the test cycles (in this case 500) according to DIN EN 12875. If a material is only labeled as »dishwasher-proof« or »suitable for dishwashers«, this is **not a precisely defined** term – it merely means that the item can generally withstand washing, but possible damage cannot be ruled out. A dishwasher-safe plastic product could therefore show discoloration, embrittlement, or hairline cracks after several wash cycles, which have not been ruled out by the manufacturer. Consumer advice therefore recommends washing sensitive plastic parts (even if declared dishwasher-proof) in the upper dish rack and using gentle programs to avoid direct heat and aggressive conditions.

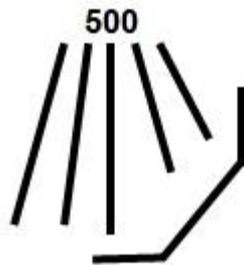


Figure 9: Symbol for dishwasher safety specifying the number of test cycles used.

Some plastics have proven to be particularly suitable for **reusable packaging**. **PP** is widely used – it is robust, dimensionally stable up to approx. 100 °C, tasteless, and generally does not contain any problematic additives. Many crates, cups, drinking bottles, and other food containers are therefore made of PP. High-density polyethylene (**HDPE**) is used for closures and thick-walled containers; it has a relatively high heat resistance (~80 – 100 °C) and absorbs hardly any water, but it can absorb odors. **PET** is used especially for reusable beverage bottles and cups for cold drinks. Repeated industrial alkali washing is not critical (Nielsen et al. 1997). However, practical experience has shown that PET is only suitable to a limited extent at cleaning temperatures above 60 °C (Bertling et al. 30.01.2025). Polycarbonate (**PC**) was also commonly used in the past, primarily for transparent applications (e.g., reusable water bottles, canteen tableware), as its high strength and temperature resistance allow it to withstand standard washing temperatures without any problems. However, PC has the disadvantage of containing **BPA** as a monomer and releasing it under certain circumstances, which is why it is increasingly being avoided in the food

sector. BPA-free copolyesters (e.g., Tritan™) have therefore gained in importance in recent years (Glausitz 2014). Polysulfone (PSU) and polyethersulfone (PES) are high-temperature-resistant engineering plastics that are also dishwasher-proof and are used in special applications (e.g., reusable baby bottles, laboratory equipment); they are also BPA-free, but (to date) significantly more expensive. However, there are also unanswered questions regarding various alternatives with regard to **migrating substances**, even if critical limit values are not usually reached (Zimmermann et al. 2019; Begley 2013; Schmid und Welle 2020).

Other criteria are relevant for **single-use packaging** that is subsequently recycled, which is why the term »recyclable« is used here. The three most important process steps in mechanical recirculating – washing/cleaning, shredding, and extruding – have very different effects on plastics. Each step leaves characteristic marks on the polymer structure, which determine the quality of the recyclate. In **hot or alkali washing**, the focus is on removing adhesive labels, grease, and beverage residues. In PET in particular, this easily leads to hydrolytic cleavage in the ester bonds: even small amounts of residual moisture or alkaline media significantly reduce the intrinsic viscosity (IV) and promote chain breaks (Bezeraj et al. 2025). PP reacts differently – it is relatively stable in aqueous chemistry, but the hot wash bath dissolves the remaining antioxidants from the outer layer. This reduces the oxidation protection for the subsequent thermal steps (Knoben et al. 2025). The subsequent **comminution** (shredding, grinding) subjects the materials to mechanical shock. High impact loads can lead to polymer chain degradation, microcracks, and crystallization, thereby altering the mechanical properties of the polymers. However, there are hardly any systematic studies of these effects. The study by Ravishankar et al. (2018) shows that even low shear forces are sufficient to cause damage. In addition, the shredding process causes plastics to be lost in the form of microplastics and nanoplastics (Brown et al. 2023; Kasper et al. 2025; Swinnerton et al. 2024). Finally, thermal, mechanical, and oxidative stresses peak during **extrusion**. In PET, the residual moisture determines whether hydrolysis (at >50 ppm H₂O) or thermal chain scission dominates; both mechanisms reduce the molecular weight and form by-products such as acetaldehyde, which is relevant to taste in beverage packaging (Shen et al. 2025). PP shows a sharp increase in melt flow rate after just a few extrusion cycles; studies report fivefold increases in MFR due to radical chain breaks and a broadening of the molar mass distribution (Krämer et al. 2024). For HDPE, analogous degradation can be demonstrated by the increase in the carbonyl index (Cruz und Zanin 2003). Washed recyclates already have oxidation times that are orders of magnitude shorter, which requires additional stabilizers or inert gas extrusion (Boz Noyan 2024). PS tends to depolymerize at temperatures above approximately 230 °C: Radical cleavages produce styrene monomers, cause yellowing, and reduce viscosity; current reviews on upcycling confirm this mechanism, as do recent analyses of thermomechanical degradation during extrusion (Pin et al. 2023; Ceretti et al. 2023). Another problem with recirculating is **cross-contamination**: If, for example, PET flakes enter HDPE streams, the impact strength of the polyolefin deteriorates dramatically because the radical degradation typical of polyester has

a catalytic effect on the PE matrix. Similar synergies apply to PP/PET mixtures (Gnoffo et al. 2025).

In summary, **the single-use cycle involves hydrolytic damage from the washing step, mechanical damage from shredding, and shear-induced and thermo-oxidative chain breaks during extrusion.** In practice, this is countered by thorough pre-drying (PET, PA), antioxidant re-dosing (PE, PP), protective gas or vacuum extrusion, and cascaded use of recyclates in less demanding target applications. In practice, it is assumed that most plastics can be **recycled about 5 to 10 times** due to contamination. In laboratory tests, higher values have also been achieved with appropriate purity or decontamination (Jin et al. 2012).

3.4 Contamination and decontamination in paper recirculating

Contamination in the input streams for paper recirculating comes both from **the paper's own** constituents – meaning the actual paper production and paper processing (printing, gluing, etc.) – and from external adhering or absorbed **foreign substances.**

Sobhani and Palanisami (2025) investigate the role of paper-inherent ingredients in composting («organic recycling»). Although paper is of biological origin and compostable, many of the additives are not. These findings can be applied to material recycling as these substances also accumulate in the material cycle. In particular, **coatings** made of PE, PP, PVDC, or PFAS, which increase the paper's resistance to environmental influences (water, grease), and mineral oil-based **printing inks** and pigments are mentioned. In addition, wastepaper from food packaging is usually not collected separately from wastepaper from other applications, especially in the private sector (blue bin; paper type 5.01 (DIN EN 643)); this fraction is assessed by the BfR as unsuitable for food applications, at least in unsorted form (Bundesinstitut für Risikobewertung 2023).

Not only does the packaging contaminate the packaged food, but conversely, **adhering food** contaminates the wastepaper stream and can hinder recirculating and lead to microbial contamination of the recycled paper and cardboard. Johansson et al. (2001) investigated the occurrence of foodborne bacteria in wastepaper processing: **Bacteria** are present, with clear seasonal dependencies (in Sweden). The process conditions, primarily the high temperature during drying, effectively reduce the number of bacteria. Adhering bacteria can migrate into food, which could be prevented by suitable barrier layers. **Health risks are very unlikely but** cannot be completely ruled out.

In Germany, paper and cardboard achieve an average reuse rate of 83% and a circulation rate of 7.7 (FEFCO 2022). This rate is often mistakenly applied to packaging with food contact. Although packaging with food contact can be collected in the wastepaper and cardboard recirculating stream, the reasons described above (mixed collection, possible contamination) mean that it cannot easily be reprocessed into food packaging, i.e., it is **downcycled.** Figure 10 shows that two-thirds of the paper produced in Germany is intended for packaging, although the proportion used for food packaging is not known.

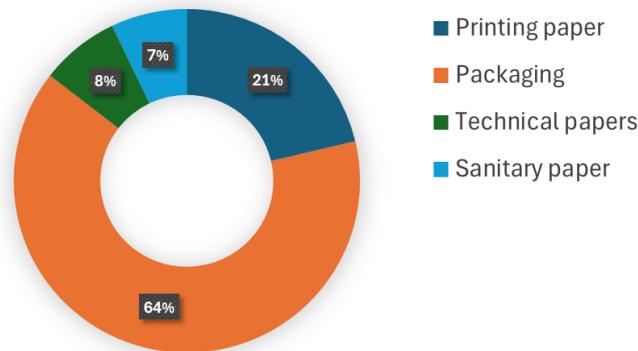


Figure 10: Main products of the paper industry and their share in overall production (Die Papierindustrie 2025)

Pivnenko et al. (2016) investigate the accumulation over time and possible removal of contaminants (**BPA, DEHP, MOH**) in the paper and cardboard cycle using material flow analysis. It can take decades to reach a steady-state final value (27 years (BPA), 31 years (MOH), 45 years (DEHP), which is why the contaminants measured today may continue to increase, as the steady state has not yet been reached. In addition, the authors examine various scenarios for reducing concentrations (optimization of collection, improvement of removal, elimination). They show that even in the optimal scenario (elimination), the removal of these substances from the paper cycle also takes a very long time (15 years (DEHP), 31 years (BPA), 13 years MOH). Despite the introduction or tightening of limit values, this time delay can severely limit the suitability of wastepaper for food applications.

When recirculating plastics for food contact applications, very high demands are placed on the origin and purity of the secondary materials (see Chapter 2). No comparable regulations are known for paper recirculating (Hirsilä 2023). However, studies and publications provide evidence that **undesirable substances accumulate** in the paper cycle and can also migrate into packaged food.

As early as 2002, Binderup et al. demonstrated the cytotoxicity of substances leached from paper, with the quantities extracted from wastepaper being higher than from fresh paper and the values from deinked paper lower than from untreated paper (Binderup et al. 2002). A research project conducted by the German Federal Ministry of Food, Agriculture, and Consumer Protection concluded that most hazardous substances contained in wastepaper that can migrate into food are not known to the authorities (CVUA Stuttgart et al. 2012). Storage tests on **the migration of mineral oil components (MOSH, MOAH)** showed that the migration of these substances significantly **exceeds** the levels classified as harmless to health by the BfR and that samples from foodstuffs **often exceed** the recommended maximum levels **by a factor of 10 or even 100** (CVUA Stuttgart et al. 2012). Printer ink components and plasticizers were also identified as problematic. Although many of these substances were depleted in the recirculating process, this was not to the extent necessary. The research group does not consider a more precise selection of specific

wastepaper fractions to be useful, as »all fractions available in relevant quantities are contaminated«, and recommends the introduction **of functional barriers** (CVUA Stuttgart et al. 2012). If these barriers are plastic layers, this would further complicate recirculating.

PFAS are used to modify certain types of specialty paper, including in the food industry, to create water- and grease-repellent properties (Umweltbundesamt 2025), which means that PFAS concentrations can also occur in paper containing recycled material. However, according to a survey conducted in 2023, only those types that are included in the BfR's positive list are still used (Umweltbundesamt 2025). Studies on **PFAS concentrations** in paper and cardboard packaging suggest, however, that these are present in quantities that are certainly problematic.¹⁸ Some types of packaging, such as flour packaging and paper bags, significantly exceed the limits of 250 ppb specified in the PPWR (Europäisches Parlament 2025) with up to 952 ppb (Langberg et al. 2024; Straková et al. 2021).

Biedermann and Grob (2010) come to a similar conclusion: hydrocarbons (up to C₂₀) can easily diffuse into food **within a few weeks** of close contact, resulting in concentrations above the recommended limits.

¹⁸ A study on single-use food packaging from six European countries showed that all of the water-repellent packaging made from paper and cardboard and plant fibers that was examined contained PFAS (Straková et al. 2021 2021). A Norwegian study also found PFAS concentrations in some other types of packaging, such as flour packaging and paper bags, that significantly exceed the limits set in the PPWR at 250 ppbEuropäisches Parlament 2025 with up to 952 ppbLangberg et al. 2024.

4 Comparison of the systems

This chapter describes the technical processes involved in recirculating. The focus is on **energy consumption** and **water consumption**. In addition, the **circularity** achieved in the recirculating of packaging (total yield¹⁹) is also considered.

4.1 Recirculation in the systems

In Germany, **single-use packaging waste** is mainly collected via various collection systems and sent for recirculating: Lightweight packaging (LWP) made of plastic, paper, cardboard, metals, and composite materials via the dual systems (yellow bag/yellow bin), paper, cardboard, and carton packaging in the private sector via wastepaper collection (blue system), and in the commercial sector with high wastepaper volumes (supermarkets, discount stores) via special collection systems, glass recirculating containers for the separate collection of glass packaging and non-deposit single-use bottles, deposit-bearing single-use bottles and cans via a bring system at supermarkets, discount stores, and beverage retailers, and the separate collection of commercial packaging waste. In addition, a lot of packaging waste also ends up in the residual waste stream, especially in the to-go sector. The return to the cycle takes place in the single-use system via recirculating. This involves several consecutive process steps aimed at efficiently collecting, sorting, processing, and ultimately reusing waste and disposing of the non-recyclable portion. Particular attention is paid to the steps involved in purifying the material flow in order to obtain high-quality recyclates. A special feature of paper and cardboard recirculating is that processing is integrated, i.e., a recyclate is not first produced and then mixed with virgin material, but rather the paper or cardboard product is manufactured in a combined process using wastepaper and fresh fiber.

For the recyclates from the single-use packaging considered in this study, the typical **types of utilization** are shown in Table 2. The classification in the »Food contact« column is based on the legal situation described in chapter 2 and the process explanations in the following chapters.

¹⁹ Circularity or total yield here refers to the proportion of material that is recycled, regardless of whether this is through reuse or recirculating. There are more complex measures of circularity, such as the Ellen MacArthur Foundation's MCI, which consider both the input and output sides, but these are not used here (EMF 2015).

Table 2: Utilization pathways for recyclates from single-use packaging and their suitability for food contact. (n.r. = not relevant)

Object	Path	Type of Utilization	Food contact
Cup (KS)	LWP	Material	No
	Residual waste	Thermal	n. r.
Cups (cardboard)	LWP	material	no
	Blue system	Thermal/material recirculating (depending on the paper mill, distribution unclear)	unclear
	Residual waste	Thermal	n. a.
Box (cardboard)	Commercial waste	Material	restricted (due to mechanical strength)

In the reusable system, packaging does not become waste but remains the property of filling companies or pool operators. Used packaging is returned via private collection systems; there is no municipal collection system. Germany has a dense network of established reusable systems throughout the country – from traditional deposit bottle pools to pools for reusable crates for fruit and vegetables, meat and baked goods, to dynamically growing to-go solutions for cups and containers. Data on the proportion of use in the reusable system exists for beverage bottles – here, the total reusable rate of 33.5% (Caye et al. 2025) remains well below the 70% target set by the German Packaging Act (VerpackG 2021). Digital, deposit-free concepts such as Vytal are spreading particularly quickly because they offer users easy borrowing and flexible returns (Cendon Garcia 2025). At the same time, German providers are increasingly exporting their reusable models to neighboring countries, while international companies such as Loop by Terra Cycle and CLUBZERØ are bringing the topic of reusables to the European retail and office catering sectors. Despite this momentum, there is still a lack of reliable, consistent data on actual usage and circulation figures, which is why politicians and researchers have so far only been able to assess the impact of these systems to a limited extent.

4.2 Conversion to the same reference values

4.2.1 Conversion to the output of the overall system

For **single-use systems**, the energy and water consumption figures below are based on the amount of material actually recycled. Mathematically, this corresponds to the proportion of total consumption that reaches a certain process stage $i \varepsilon_{i-1}$, multiplied by the input-related energy and water consumption of this stage $E_{m,i}$ bzw. $V_{m,i}$, divided by the **circularity** ε_{ges} . Circularity corresponds to the total yield across all cycle steps or the reuse rate in production, without taking into account whether the quality is sufficient for use in the original application in terms of food contact suitability or material properties:

$$E_{m,Output} = \frac{\sum_{i=2}^n (\varepsilon_{i-1} \times E_{m,i})}{\varepsilon_{ges}} \quad (1)$$

$$V_{m,Output} = \frac{\sum_{i=2}^n (\varepsilon_{i-1} \times V_{m,i})}{\varepsilon_{ges}} \quad (2)$$

The calculation of the specific, output-related energy requirement for LWP collection serves as an example. The process steps of sorting, processing, and shaping were taken into account, with the last step assumed to be loss-free, so that the proportion of consumption reaching the process stage is equal to the circularity. Using the data from Table 5, and the above equation, for example, the result is:

$$E_{m,Output;LVP} = \frac{0,648 \times 0,07 + 0,75 \times 0,312 + 1,30 \times 0,232}{0,232} = 2,52 \frac{kWh}{kg}$$

The specific, output-related water requirement according to equation 2 is calculated analogously.

For **reusable systems**, the proportion of the total circulating packaging material that is sent for cleaning corresponds to the **return rate**, while the circularity corresponds to the return rate minus the proportion of crates discarded during cleaning. This form of circularity neglects the fact that the discarded packaging can still be recycled, albeit with different consumption values, which is why this aspect is not taken into account here. As a rule, shrinkage and discarding are combined in the circulation number n .

$$E_{item,Output} = \frac{E_{item,input}}{\varepsilon_{return} \times (1 - \varepsilon_{Sorting\ out})} \approx \frac{E_{item,input}}{\left(1 - \frac{1}{n}\right)} \quad (3)$$

$$V_{item,Output} = \frac{V_{item,input}}{\varepsilon_{return} \times (1 - \varepsilon_{Sorting\ out})} \approx \frac{V_{item,input}}{\left(1 - \frac{1}{n}\right)} \quad (4)$$

4.2.2 Conversion to nominal volume as reference value

The consumption values determined below for recirculating processes in a single-use cycle, which are given in kWh/kg or L/kg output, as well as the cleaning processes in a reusable cycle, which are normally related to a single rinse cycle or a single item to be rinsed, must be converted to a **uniform reference value** that allows for a meaningful comparison. In this study, the nominal filling volume is used for this purpose. Other options would be conversion per mass of packaging material or the surface area to be cleaned. The nominal filling volume was chosen as the reference value because it best represents the core function of the packaging, namely the absorption of a corresponding quantity of goods. This assumption does not necessarily correspond to the overall benefit of packaging, as it neglects the fact that, for example, reusable systems are often more break-proof or can be equipped with additional functions (e.g., RFID) due to non-destructive recirculating.

Figure 11 and Figure 12 show the ranges of mass and nominal volume for boxes and cups found in the literature, differentiated between single-use and reusable. In the evaluation of single-use cups, those made of cardboard and

plastic were taken into account, as these did not show any systematic differences in the ratio of mass to volume; for single-use boxes, only cardboard was taken into account. Reusable systems were always made of plastic. The compensation lines passing through the origin can be used to make rough estimates of the **specific material costs** (mass/nominal volume corresponds to the slope $\Delta m/\Delta V$ of the respective line) for each type of packaging. These are used for single-use systems to convert mass-related values into volume-related values (equations 5 and 6).

$$E_{V.Output} = E_{m.Output} \times \Delta m/\Delta V \quad (5)$$

$$V_{V.Output} = V_{m.Output} \times \Delta m/\Delta V \quad (6)$$

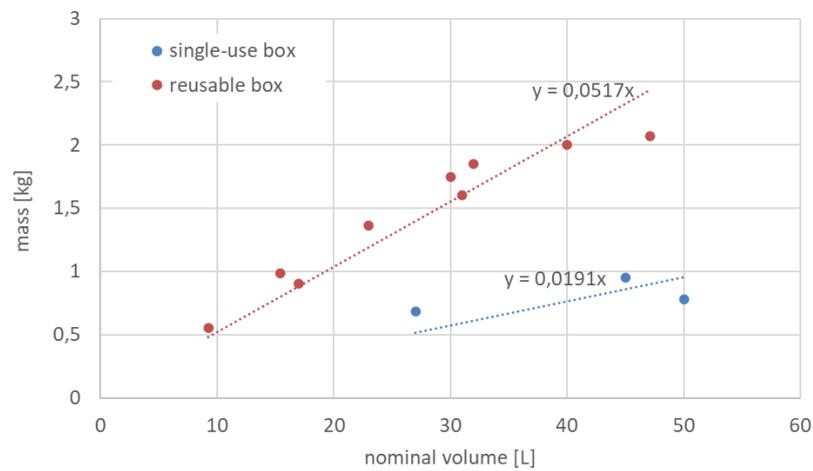


Figure 11: Mass over nominal volume for single-use (cardboard) and reusable boxes (PP, HDPE) [Own representation based on data from various online platforms]

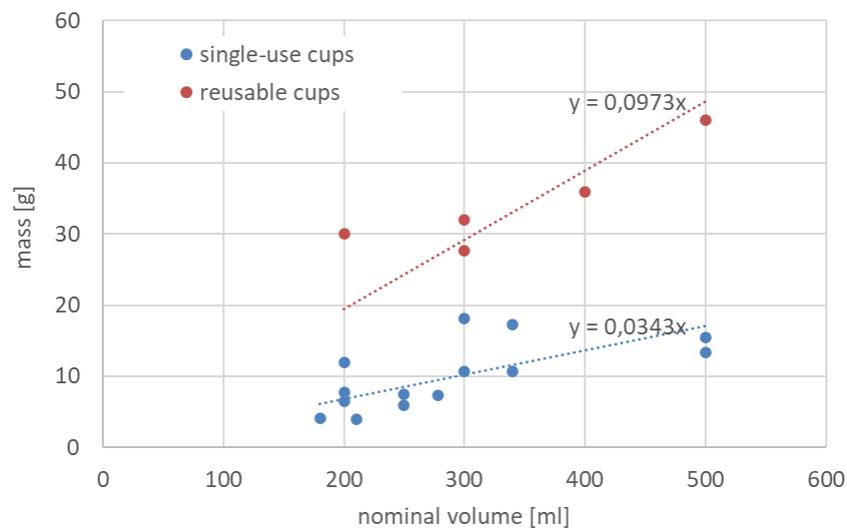


Figure 12: Mass over nominal volume for single-use (cardboard, coated cardboard, PE, PET, PS) and reusable cups (PP) [Own representation based on data from various online platforms]

From this representation, the conversion factor from material to nominal volume for single-use packaging used in the following is derived: 0.0191 kg/L packaging weight for single-use boxes and 0.0343 kg/L for single-use cups, which forms the basis for the comparisons in the following subchapters.

Table 3: Material demand of single-use and reusable packaging

Object type	Single-use	Reusable	Ratio Reusable / Single-use
Box	0.0191 kg/L	0.0517 kg/L	2.7
Cup	0.0343 kg/L	0.0973 kg/L	2.8
Ratio Cup/box	1.8	1.9	

In addition, Table 3 shows the **ratio of material costs** for the same volume for the two systems and the two types of packaging. On the one hand, it can be deduced that the material costs for reusable packaging are about three times higher per volume than for single-use packaging.²⁰ Even if this material cost is justified by the high circulation figures of reusable systems, it must be taken into account in a fair comparison (see chapter 5.4).

Furthermore, Table 3 clearly shows that the material demand per volume approximately double from large boxes to small cups, regardless of whether they are single-use or reusable systems. These ratios are relevant when comparing the actual circularity achieved in Chapter 5.4 and the efficiency of cleaning cups and boxes in Chapter 5.5.

For **reusable systems**, the values per wash cycle must be converted to the nominal volume. Since explicit information on the volumes of the cleaned containers was available for the reusable cleaning processes, it was possible to determine the volume-related energy consumption directly and use this to determine the average volume-related water and energy consumption (see chapters 4.5.2 and 4.5.3).

4.3 Recirculating of single-use plastic packaging

Production, waste generation, and material recirculating

In the packaging sector, a total of 3.84 million tons (or megatons, Mt) of plastic were used in Germany in 2023. The volume of **post-consumer plastic waste** in the packaging sector amounted to **3.07 Mt** in the same year, corresponding to 79.9% (BKV 2024). The difference between consumption and waste can be explained by export surpluses, long-term retention in households, and, to a

²⁰ This analysis does not take into account the fact that the material costs for reusable products are spread over many uses. If the evaluation of the systems were based solely on material costs, reusable systems would already have an advantage after three cycles.

lesser extent, littering. Nevertheless, these quantities are not available to the circular economy. The recorded waste is divided into 1.97 Mt of household packaging waste and 1.11 Mt of commercial waste (BKV 2024). Of the packaging waste collected, a total of **approximately 2.49 million tons, corresponding to 64.8% of material recirculating**, is sent for recirculating via the LWP path, the separate collection of single-use bottles, and separately collected commercial packaging. The difference between the waste collected and that sent for recirculating goes directly to energy recovery, is found in the household sector, mainly in residual waste, or is exported without proof of recirculating. In the case of commercial waste, the losses are found in mixed commercial waste and mixed construction and demolition waste.

Of the quantities supplied, **1.59 million tons (41.4%)** are **actually recycled** after sorting according to BKV (LWP path 0.63 Mt, single-use bottle collection 0.33 Mt, separate collection of commercial packaging waste 0.63 Mt) (BKV 2024)).

4.3.1 Generic consideration of lightweight packaging (LWP)

The LWP path is described in more detail below based on the quantities fed into it, as the effort and circularity involved differ significantly from, for example, the recirculating of the largely single-type single-use bottle fraction or separately collected commercial waste, but at the same time this path is particularly relevant for cup recirculating.

I Sorting

In the first step, sorting, after the waste bags have been opened and, if necessary, roughly shredded (shredder), the waste is separated by size using **rotary screens**. Ferrous metals and foils are then recovered using **air separators** and **magnetic separators**. This is followed by **eddy current separators**, ballistic separators, and **NIR separation**, before final manual re-sorting takes place. With regard to plastics, fractions with a high proportion of HDPE, PET, PP, PS, foils, and mixed plastics are usually produced, which must meet the minimum specifications set by the DKR. The fractions are baled with steel strapping and sent for further processing (Bulach et al. 2022; Kaitinnis 2019; Schyns und Shaver 2021; Kasper et al. 2025).

Knappe et al.(2021) assume a slightly higher yield from sorting of approximately 60%. For PE plastics, this figure is approximately 50%, for PP 42% and for PS 38%. Approximately 70% of PET is sorted as mixed fraction. Of the recovered plastics, more than half (50.4%) end up in the mixed fraction, which is mainly used as a substitute for wood or concrete. Approximately 49.6% are found in target fractions aimed at recovering individual polymers.

A detailed life cycle assessment study by the Öko-Institut on the performance of dual systems shows a material recirculating rate of 49.4% across all plastic fractions for the sorting stage (Bulach et al. 2022). Significant losses arise from

the mixed plastic fraction, which consists of 75% plastic, and the sorting residues (which still contain 49% plastic), both of which are sent for incineration (Bulach et al. 2022).

Data from Kaitinnis on a sorting plant operated by the Meilo company also confirm these figures for a single plant (Kaitinnis 2019). Overall, sorting usually results in several fractions, most of which consist mainly of plastic. The DKR catalog comprises 20 different specifications; the sorting spectrum used is not uniformly regulated nationwide (Kasper et al. 2025; Knappe et al. 2021). The individual plastic fractions differ significantly in terms of achievable yields, with the values for PE, PP, and PS above the average material recirculating rate and those for PET significantly below it.

With a sorting yield of approximately 49.4% relative to the input, the overall **circularity after sorting is still 31.7%** relative to the original plastic consumption (see Figure 13).

Sorting is usually carried out **dry**, with **energy consumption** mainly comprising electricity for the separation technology, which is stated as approx. **0.05 to 0.09 kWh per kilogram of input material** (Bulach et al. 2022; Kaitinnis 2019; Schyns und Shaver 2021; Kasper et al. 2025; Jeswani et al. 2021; Knappe et al. 2021; BKV 2024).

II Processing (shredding, washing, drying) and regranulation (including melt filtration)

Only established mechanical processes are considered here in the context of processing; alternative routes such as chemical recirculating are not taken into account due to their low practical relevance to date.

The sorted fractions pressed into bales are fed into a processing plant. There, the plastics are first coarsely shredded and then separated from metals using magnetic and eddy current separators, and from light and heavy materials using air classification and float-sink separation, before being divided into density-specific fractions. The two important packaging plastics, PE and PP, cannot be separated by flotation due to their very similar densities. **Optical sorting methods** are required here (Knappe et al. 2021). The material is then further shredded using **wet grinders** to produce flakes. These are **washed** in two stages, **first cold and then hot**. When cleaning the flakes, it is also important to remove odors. This requires cleaning agents that are specifically adapted to the type of polymer (Roosen et al. 2022). The flakes are dewatered and dried. Some of the flakes are separated as fine material or agglomerated and used, for example, as a concrete substitute. The main stream of flakes is separated into different colors by optical sorting (VIS, RGB) and separation using compressed air nozzles.

The cleaned ground material that is not used directly as agglomerates or additives (such as EPS) is regranulated in the next step using **an** extruder (Bulach et al. 2022). Fresh material or additives may be added to counteract thermo-oxidative and shear-induced chain degradation, branching, and cross-linking. Not

only are residual foreign polymers in the sorting fraction a problem, but also substances that are still present in the target plastic itself from its first life: pigments, printing inks, labels, adhesives, release agents, etc. These can catalyze degradation reactions or cross-linking (Schyns und Shaver 2021). The use of melt filters has become established as a means of removing contaminants. These are perforated filters or wire mesh through which the melt must pass. This step leads to further, albeit minor, losses of polymer and increases energy consumption.

A recent study by Kasper et al.(2025) shows that around 15% of the target material is lost during the recirculating of polypropylene. The largest leaks occurred during wet grinding, friction washing, and mechanical drying. Overall, about **3.9% of the input** ended up **as microplastics in the wastewater stream**. The microplastics are separated together with other contaminants using a flocculant in a flotation plant (97–99%) (Kasper et al. 2025). Jeswani et al.(2021) report a yield of 67% for the treatment and regranulation step, but do not specify the proportion of contaminants in the input. Knappe et al.(2021) assume an 85% yield for the processing and regranulation step, Larrain et al.(2021) report values ranging from 82 to 94% for different types of polymers. Due to the chemical and physical forces acting during extrusion for regranulation and the downstream processing, mechanical recirculating often leads to a reduction in tensile strength and elongation at break for PP, tensile strength for HDPE, elongation at break for LLDPE, impact strength for rPP, and a variety of other problems for PET. (Schyns and Shaver 2021). **This deterioration in polymer properties, together with residual contaminants, means that virgin material cannot be replaced 100% by recycled material.** Substitution factors of 95% or lower are common (Bulach et al. 2022). Jeswani et al.(2021) calculate a substitution factor of only 50% based on market prices.

In the following, we base our calculations on data from Bulach et al.(2022), which allow us to estimate a yield of 73% across the entire process chain from sorting output to secondary raw material for the processing and regranulation stage (Table 4). In relation to the amount originally produced, **23.2% remains** in the cycle **after processing and regranulation**.

Meyer et al.(2009) investigated the level and structure of energy consumption in recirculating companies in North Rhine-Westphalia. They give values between 0.19 and 0.45 kWh/kg for electricity consumption, with electricity consumption accounting for over 95% of final energy consumption. However, they do not distinguish between companies that operate sorting or processing plants, nor whether the end products are sorted fractions, agglomerates, regranulates, or molded parts. Without information on the process steps and the achievable yield, these data can therefore only provide a rough guide. Gandhi et al.(2021) used SIMAPRO 7.1 to model the fossil energy requirement at only 0.19 kWh per kilogram of recycle for HDPE. Larrain et al.(2021) carried out a detailed techno-economic modeling of processing and regranulation (excluding collection and sorting); They calculated energy and freshwater consumption of 0.72 kWh and 0.28 L for PP, 0.60 kWh and 0.15 L for PS, and 0.93 kWh and 0.34 L per kilogram of input for PE films.

Values of 0.46 to 0.71 kWh and 0.5 L per kilogram of input are typical for electricity consumption and freshwater requirements during processing and regranulation (Bulach et al. 2022; Knappe et al. 2021). The polymer-specific values from Bulach et al.(2022) are compiled in Table 4. Meyer et al.(2009) attribute the high specific energy consumption of plastics—compared to cardboard and metals—to the effort involved in shredding. However, it can be assumed that the effort required to heat the cleaning water and the subsequent drying also contribute significantly to the total energy consumption (Gandhi et al. 2021). The available data is ultimately based on personal information and data from the DSD from 2015 (Dehoust et al. 2016), which, however, refer to other older sources and are hardly completely verifiable. There is data in the literature that confirms the energy consumption but indicates rather higher water consumption. Uekert et al.(2023), for example, report electricity consumption and freshwater requirements of 0.43 kWh and 0.87 L for HDPE, 0.83 kWh and 1.00 L for LDPE, and 0.43 kWh and 1.06 L for PP, per kilogram of output. Our own surveys at a modern processing and regranulation plant suggest that improved yields can be expected in the future, accompanied by rising consumption values (data cannot be published for reasons of confidentiality).

Table 4: Water and energy consumption per kilogram of input into LWP processing, effective yield (corrected for the substitution factor)

Target material	Energy requirement [kWh/kg]	Water requirement [L/kg]	Effective yield [%]
PE, PP	0.72	0.5	86
PET (from LWP)	0.69	0.5	87
PS	0.58	0.5	61
Sheets	1.23	0.5	81
MKS	0.71	0.5	40
Average value across all fractions	0.75	0.5	73

III Conversion: injection molding, blow molding, etc.

Recirculating produces regranulates. To close the cycle, reshaping is necessary. Depending on the application, this may involve injection molding, extrusion, blow molding, or other processing techniques. Typical values for energy consumption can be found, for example, at Kent (2011) :

- Injection molding: 0.9 to 1.6 kWh/kg
- Extrusion: 0.4 to 0.6 kWh/kg
- Blow molding: 2.0 to 2.6 kWh/kg

This energy thus accounts for a significant proportion of the energy consumed throughout the entire cycle. Cottafava et al. (2021) et al. give values of 1.21

kWh for PP, 0.93 kWh for PLA, and 1.9 kWh for PET per kilogram of production volume in their study on cups. These values are within the ranges shown above.

IV Overall view

The plastic flow in the LWP path is reduced **to 23.2% of the original mass** over the cycle from production to **reuse of the recycle** (Figure 13).²¹

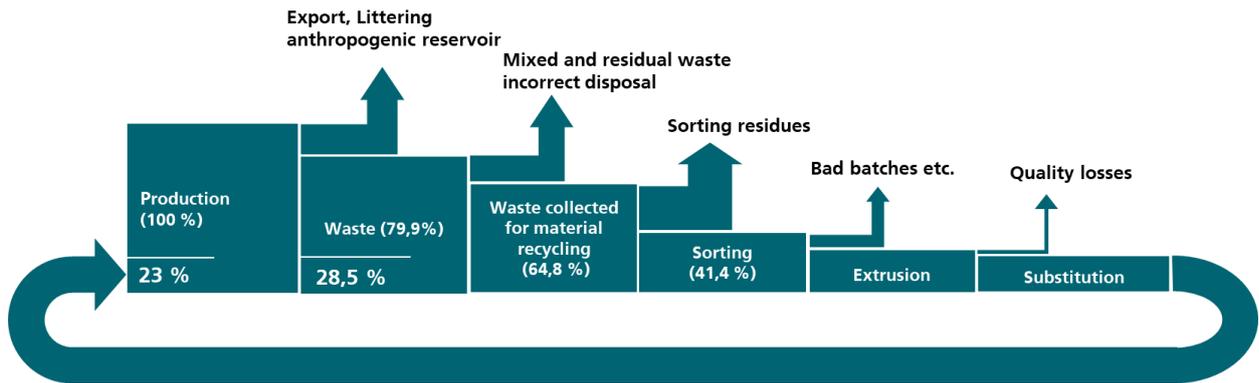


Figure 13: Plastic losses along the single-use cycle. The values in brackets refer to the proportion of production that is still available after the respective step. The values below the line correspond to the proportion of production or the amount of waste generated.

If the typical energy and water consumption per stage is applied to the output achieved, the final energy requirement is 2.52 kWh and the freshwater requirement is 0.68 L per kilogram of recycled end product (Table 5). This analysis does not take into account the fact that by-products are also recycled (especially for energy), but it is nevertheless useful, as material recirculating is the primary goal of circularity.

Table 5: Input-related energy and water requirements per process step as well as total consumption and circularity related to the end product (for calculation see chapter 4.2).

Target material	Typical energy requirement [kWh/kg]	Typical water requirement [L/kg]	Percentage of production reaching this level [%]
based on input into the stage			
Sorting	0.07	0	64.8
Processing, incl. regranulation	0.75	0.5	31.7
Shaping	1.30	0	23.2
Based on output			
Total	2.52	0.68	23.2

²¹ This is true if we assume that the distribution of cup quantities made of PE, PP, PS, and PET roughly corresponds to the distribution in the entire LWP stream

4.3.2 General considerations regarding separately collected single-use plastic waste

The separate collection of single-use packaging is well established for beverage bottles, for example, and also in commercial settings, such as for agricultural films or canisters. In principle, this can be expected to result in lower losses during collection and sorting, less contamination, and correspondingly significantly higher input into processing. While the **material recirculating rate** from LWP sorting is only 49.3% based on the incoming plastic mass, it reaches **88.1%** for **single-use beverage bottles** and 85% for separately collected commercial waste (BKV 2024). Life cycle assessment data from the life cycle assessment study on the »recyclable bottle« has not yet been published, so an evaluation analogous to the analysis of LWP is not possible. Uekert et al. (2023) give values for the mechanical recirculating of PET bottles of 0.43 kWh/kg for energy consumption and 1.00 L/kg for water consumption in relation to output. The efficiency of waste collection and delivery for material recirculating is not reported in detail in their study; for California, a collection rate of only 30% is given as an example. The collected bottles are quite heavily contaminated, at 12 to 14%. The authors state the yields (»material retention«) from sorting for PET as 57 to 90%.

The collection of single-use beverage cups, e.g., PET cups, via the collection systems for single-use bottles could significantly increase the yield and reduce consumption data. To date, however, reverse vending machines are only available for reusable cups (Utopia 2023).

4.3.3 Single-use cups made of PP, PS, and PET

Single-use plastic cups are mostly made of PP or PS and, to a lesser extent, PET. The typical values for energy and water consumption determined above are therefore used below.

At the end of their life, the cups must be recycled correctly via the LWP path. Optimistically, one could therefore assume that the unrecorded proportion of single-use cups corresponds to the total amount of waste. However, since single-use cups are mainly used in **the to-go sector**, it is likely that they are **disproportionately** disposed of **via the residual waste path** and not disposed of properly at all (littering). The actual **yield of recycled material** is therefore likely to be rather low. A recent Germany-wide sorting analysis of LWP collections by Pforzheim University found that cups accounted for 6% of the total (Auer et al. 2025), but only an estimated 1.2% of these were single-use to-go beverage cups, which consisted mainly (77%) of plastic (Schill 2025). With an LWP collection volume of 2.51 Mt/a (see chapter 4.2) and an estimated total volume of 28,000 t/a of single-use to-go beverage cups, of which 8,400 t are made of plastic (see chapter 1.5.1), this would result in a collected quantity of approximately 1,800 t of single-use beverage cups in the LWP collection, or a collection rate for KS cups of 16.5%. This would indeed be significantly lower than the average collection rate for plastic packaging of 64.8% stated above. Furthermore, PET from the LWP collection, unless it is in the form of beverage

bottles, is still not recycled (Knappe et al. 2021). Cups made from rPET therefore mainly use material from the separate collection of beverage bottles.

Furthermore, it should be noted that the recyclates produced today from LWP recirculating are **not used for food contact**. The only exception is PET beverage bottles separated from the LWP stream. Although single-use cups disposed of via the LWP pathway can replace primary raw materials in secondary applications, this cannot be considered closed-loop recirculating at present. It can be assumed that energy and water consumption will continue to rise disproportionately if the materials are to meet the requirements for food contact. In the following, **a maximum and minimum total yield of 23.2% and 0%** is therefore assumed **for cups. Based on the nominal volume**, typical values **for single-use plastic cups are shown** in the table below.

Table 6: Consumption values and circularity in the recirculating of single-use plastic cups

Criterion	Value
Freshwater consumption [L/L]	0.023
Final energy demand [kWh/L]	0.086
Circularity (downcycling possible)	23
Circularity (no recirculating if FCM required)	0

4.4 Recirculating of single-use packaging made from paper and cardboard

4.4.1 Generic consideration

The basic material for modern paper production is **wood fibers**, which are obtained either mechanically (wood pulp, wood chips) or chemically (cellulose). Wood has the typical advantages and disadvantages of renewable raw materials. On the one hand, the material is carbon dioxide neutral (CO₂-neutral), as CO₂-absorption during growth and CO₂-emission during combustion/composting are equal. In addition, the paper industry can use the biogenic waste generated during paper production to generate process heat and electricity for paper production, thus producing very low CO₂-emissions. However, the high consumption of wood also places considerable ecological pressure on the resource »forest«, an ecologically relevant effect that is not further considered in this study.

Paper recirculating has been established for decades and is integrated into the production process. Figure 14 shows an overview of the paper manufacturing process with the primary and secondary raw materials required and the resulting residues. There are two main ways of obtaining secondary raw materials from paper and cardboard: either the material is obtained **from the LWP fraction** of the yellow bin, or it is collected in the blue system **of separate waste-paper collection**. Plastic-coated paper and cardboard food packaging (salad bowls, coffee-to-go cups, baking paper, bubble envelopes, etc.) is plastic-

coated and must be recycled via the LWP route (yellow bin). Heavily soiled paper and cardboard packaging (e.g., pizza boxes), on the other hand, must be disposed of in the residual waste; it is not recycled. The LWP route is a positive sorting process (paper and cardboard is removed from the stream); the blue system route is a negative sorting process (impurities are removed).

As can be seen in Figure 14, the wastepaper used consists of **various fractions**. It is mainly pre-sorted wastepaper that has been sorted by upstream sorting plants. However, some paper mills specializing in packaging paper also accept unsorted wastepaper and, depending on the market price, lower-quality paper and cardboard from LWP sorting, which has been separated in LWP sorting plants using NIR separators. Some specialized plants with long suspension times can also process liquid cartons (FKN) and plastic-coated cups from LWP.

In sorting plants, paper and cardboard from the blue collection is first separated and sorted by size. Contaminants are also sorted out and assigned to the fine fraction, which must be recycled or disposed of separately. Cardboard and cardboard packaging are then separated from graphic paper using spike systems. Spike systems²² separate cardboard and paper according to their stiffness: cardboard is impaled by a spiked roller and thus lifted out of the stream, while the paper falls down. The fractions are passed on to paper mills as **bales** in groups in accordance with DIN EN 643.

At the paper mill, the paper is then moistened to separate the fiber composite («suspension process»). Trough digesters or digesting drums are used for this purpose. Foreign matter («rejects») consisting of plastic films, textiles, wires, or heavy metals are separated from the paper composite and removed. Multi-stage cleaning processes are usually necessary to achieve the required purity. Printed wastepaper must first undergo a **deinking process** to clean the fibers of printing ink and brighten them. Cardboard does not usually require deinking. Fresh fibers are added to the pulp produced, and the fibers are skimmed off in a thin layer on a screen, dewatered, and finally dried to obtain new paper and cardboard materials (Grummt und Fabian 2023). As a rule, the freshwater requirement for paper and cardboard production from fresh fibers is around 40 L/kg, which is about four times higher than for production from recycled fibers, which requires less than 10 L/kg. However, the energy requirement for fresh fibers is slightly lower at less than 1 kWh/kg than for recycled fibers at approximately 1.25 kWh/kg (FEFCO 2024).

²² e.g. Grumbach and Petermann: <https://www.gupgmbh.de/en/paperspike/> (accessed on 09/22/2025)

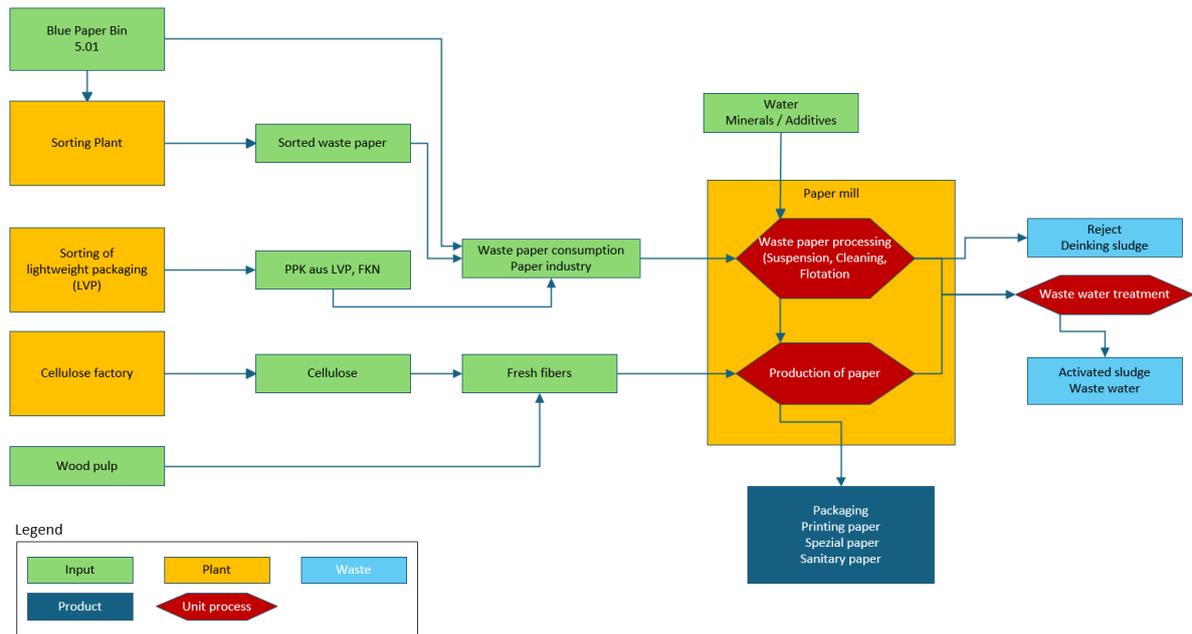


Figure 14: Overview of the paper manufacturing process and the use of recycled paper and fresh fibers [Own representation based on (Grummt 2022; LUBW 2020)]

The paper industry mainly uses wastepaper as a fiber material; the **wastepaper utilization rate** in 2023 was **83.1%**, which describes the use of wastepaper in relation to total paper and cardboard production, but not the proportion of secondary fibers in the total fiber quantity. The remaining 16.9% of the fibers used are fresh fibers, mainly consisting of pulp and, to a lesser extent, wood pulp, e.g., in the production of newspapers (Umweltbundesamt (Hg.) 2024).

In a monitoring report for 2023, the European Paper Recirculating Council reports a wastepaper utilization rate of 79.3%; for waste recycled within Europe, this rate fell to 67.1% (EPRC 2024). There is no breakdown of the amount of wastepaper lost from integrated production processes and the amount of pre-consumer recyclates used; both proportions reduce circularity.

An evaluation of international data from the CEPI (2025) for the 18 member countries shows a collection rate for paper waste for recirculating, adjusted for export and import quantities, based on the amount of paper and cardboard consumed, of 68%. Furthermore CEPI (2025) states in its data for the transformation of wastepaper into usable fiber material («pulp») a recovery rate of 73.3%. No further explanation is given as to what these transformation losses are attributable to. This results in a total recycled fiber utilization rate of 49% (not taking into account non-fibrous paper components).

Figure 15 shows the **paper and cardboard material cycle**. In particular, it can be seen here that there are **different wastepaper rates** and that it is often unclear in the literature which of these rates is being referred to. The wastepaper return rate (wastepaper generation/paper consumption) is 85.1%, i.e., 14.9% of the paper used is lost during the use phase. These losses are not the

direct responsibility of the paper industry, but in order to compare circularity, this must be taken into account, as is also done for reusable products via the return rate.

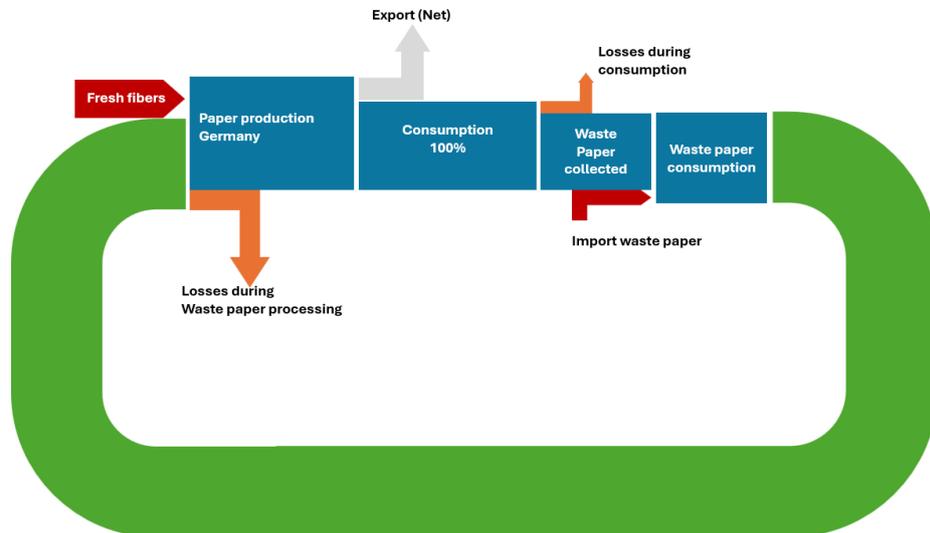


Figure 15: Paper and cardboard recirculating cycle in Germany (according to the German Environmental Agency (Umweltbundesamt (Hg.) 2024) and own calculations)

In principle, paper recirculating is limited by the degradation of fibers during the manufacturing or recirculating process, so that typically **5–7 cycles** are **achieved**, with quality deteriorating from cycle to cycle. This is counteracted by the continuous addition of fresh fibers, which ensures consistent quality. When producing new paper from wastepaper, losses of 10% (packaging paper) to 20% (newsprint) occur because a certain proportion of the recycled fibers are too short and must be removed (Höke 2013). These losses cannot be reduced by optimizing the process, but are inherent in the material.

Circularity cannot be clearly determined because, unlike with plastic, no recycled material is produced; instead, cardboard is produced directly from wastepaper and fresh fibers in a single step. In addition, the domestic German cycle is not completely closed due to imports and exports of paper and wastepaper. Assuming that these materials do not differ from those within Germany and assuming an average loss rate of 15%, it can be calculated that a proportion of the paper consumed in Germany

$$\varepsilon_{\text{ges}} = \varepsilon_{\text{Erfassung}} \times (1 - \varepsilon_{\text{Verlust}}) = 0,85 (1 - 0,15) \approx 0,72 = 72 \% \quad (5)$$

is reprocessed into paper.

For cardboard, FEFCO states **an average wastepaper usage rate of 88% in Europe** for **2023** (FEFCO 2024). The Corrugated board 2021 data set in the MLC database (Sphera 2025) assumes a lower value of 83%. **If pre-consumer recirculating is excluded, the wastepaper usage rate drops to 77%** (FEFCO 2024).

For cardboard boxes such as fruit and vegetable crates, which must be very strong and stackable, paper types with a very low recycled content are usually used (semichemical fluting and kraftliner). Therefore, the use of the average (high) recirculating rate can lead to a significantly positive assessment (see also the LCA by Castellani et al. (2022)). In contrast, corrugated liner and testliner are produced almost exclusively from wastepaper. The use of wastepaper amounts to 1.09 tons per ton of product, which is greater than 100% because a proportion of the fibers has to be removed during the process for quality reasons (FEFCO 2018, 2024). For 2023, FEFCO provides data according to Table 7 for various types of cardboard. The recycled material usage rates are reduced when FEFCO's type-specific pre-consumer recycled materials are excluded from the calculation. It can also be assumed that part of the wastepaper used ends up in the reject stream. This further reduces the effective reuse rate.²³

With regard to the achievable **circularity**, it must also be taken into account that food contact requirements significantly restrict the use of recycled materials. According to the BfR recommendations, various limit values must be observed, which are particularly difficult to comply with for recycled materials based on printed wastepaper. Since 2017, there has been discussion about a barrier requirement for food contact materials based on paper and cardboard (BMEL 2017; Bundesinstitut für Risikobewertung 2023). Appropriate barriers are now common practice when using recycled fibers, even without the implementation of the proposed regulation (WestRock 2025; MM Group 2025). This barrier could significantly limit recyclability. However, there are no systematic studies on the proportion of wastepaper in food contact materials or on the correct disposal of paper and cardboard packaging with barrier layers (yellow or blue system), nor is there any explicit labeling of packaging in this regard.

Table 7: Freshwater requirements and energy consumption in the production of various types of cardboard, as well as the recycled material usage rate achieved, data from FEFCO (2024), supplemented by our own estimates based on data on pre-consumer recycled materials and rejects

Criterion	Semi-chemical Fluting	Kraftliner	Recycled fluting	Testliner
Market shares	2.4	15.5	36.1	45.9
Freshwater requirement [L/kg]	38.16	31.41	8.13	8.13
Final energy requirement [kWh/kg output]	1.10	0.99	1.24	1.24
Recyclate usage rate	14.4	25.3	109	109
_minus pre-consumer recycled materials (own estimate)	12.5	23.2	100.8	100.8
_minus rejects (own estimate)	11.7	22.4	99.5	99.5

Table 7 also shows the consumption values for final energy and freshwater. Based on a linear extrapolation (to 100% recycled content, see chapter 9 Appendix C), **the typical energy requirement for recirculating wastepaper**

²³FEFCO (2024) continues to provide macro balances of the use of primary and recycled fibers for the individual types of cardboard. These differ from the inventory data; in the case of kraftliner, they are even lower than the corrected values in Table 7.

for cardboard production can be estimated **at 1.24 kWh/kg and the fresh-water requirement at approx. 7.8 L/kg** in relation to output. Die Papierindustrie (2025) in Germany specifies slightly higher values for both specific water consumption (here as wastewater) and energy consumption, at 8.9 L/kg and 2.7 kWh/kg, respectively. However, as these are overall balances for the industry, the system boundaries are not clear.

The situation for single-use paper cups and cartons is examined in detail below.

4.4.2 Single-use cups made of cardboard

Single-use cups made of cardboard, usually coated with PLA or PE, should preferably be disposed of by end consumers in **the yellow bag**. In LWP sorting plants, they are then assigned to the »paper and cardboard from LWP« fraction. Due to contamination, this fraction is of inferior quality for recirculating. The likelihood of this fraction being recycled therefore depends on the current market situation (Kölmel 19.12.2024). Furthermore, according to a recommendation by the Bundesinstitut für Risikobewertung (2023), paper mills that produce primary or secondary packaging for **foodstuffs** are **not** permitted to use **paper and cardboard from multi-component collection** and therefore also not from LWP collection. However, this type of packaging often leads to **incorrect disposal**, with consumers throwing the **cups into the wastepaper**, so that at least in paper mills that do not sort out this packaging because they have a trough suspender, recirculating on a small scale can occur. In a study by Grummt und Fabian (2023), 11 out of 45 paper mills stated that they sort out to-go cups from the stream.

In addition, single-use cups from to-go applications are often disposed of in residual waste, as separate waste collection is usually not offered in public areas; they are then completely lost for recirculating. Environmentally open to-go applications also facilitate littering, although there are no quantitative findings on this. Individual manufacturers offer a take-back service for single-use paper cups (emptied, stacked, in cardboard boxes) (Papstar 2025b). The extent to which such offers are accepted is not known.

Grummt und Fabian (2023) estimate the probability of paper and cardboard from LWP being recycled into high-quality products at between 25.5% and 66.8% for Germany. The spread is explained by the uncertainty resulting from the closure of an important German paper mill. The authors generally assume that this fraction is heavily contaminated, has a short shelf life, and is prone to mold growth, meaning that high-quality recirculating is not possible. In addition, they emphasize once again that paper mills that recycle the paper and cardboard fraction from LWP collection are not allowed to manufacture products for food contact according to the BfR recommendation. The extent to which these average values apply to all paper and cardboard packaging and thus also to paper and cardboard single-use cups is unknown.

Potting und van der Harst (2015) conducted an international meta-analysis of life cycle assessment studies for single-use and reusable cups. In all life cycle assessments, incineration or landfill was assumed for the end-of-life treatment of

coated paper cups. **In a further meta-analysis by Lewis et al. (2021), it is emphasized that paper cups perform well when recirculating rates of 80% or more are assumed in scenarios; however, these scenarios obviously do not correspond to practice.** Joana Almeida et al.(2018) assume a recirculating rate of 21% for PE-coated paper cups in Europe, Foteinis (2020) give a recirculating rate of only 0.25% for the same cups in the UK based on consumption. Lewis et al.(2021) highlight in a meta-analysis that none of the studies examined considered littering as a typical—albeit undesirable—EoL option.

Two companies state that a typical cardboard quality for cups and other take-away food containers is made from virgin fibers and coated with polyethylene (Stora Enso 2025; Huhtamaki 2025). Pladerer et al.(2008a) also assume that the cups are made from fresh fibers and are completely thermally recycled. Some manufacturers offer paper and cardboard cups that are made entirely from paper and cardboard and could therefore be sent for separate collection (CupPrint 2025; Papstar 2025a). The extent to which this is recognized by consumers and understood in terms of the correct disposal method is unknown. At the same time, however, this is not a closed cycle, as recirculating is not aimed at producing new cups, at least (Papstar 2025a, 2025b). Individual manufacturers advertise double-walled products that contain recycled materials in the outer layer without specifying their exact origin and quantity (CupPrint 2025).

None of the above values take into account the losses described above during the use phase or losses due to a decrease in fiber quality. If these are taken into account and it is assumed that losses via littering or disposal via the residual waste stream amount to 50%²⁴, then assuming an average sorting and processing yield based on the values from Grummt und Fabian (2023), **a realistic value for circularity would be 17%. The minimum circularity would be 0%** if only fresh fibers were used due to food contact requirements.

Specific values for energy and freshwater consumption in recirculating have rarely been reported in the literature; instead, aggregated life cycle assessment data sets are generally used. Scenarios on the relevance of water and energy consumption in comparative life cycle assessments referred to variations in the reusable system (Ligthart 2007; Martin et al. 2018). The effort involved in manufacturing cups from cardboard was not taken into account, and there are still uncertainties regarding the correct type of cardboard for cup production (Ligthart 2007). Cottafava et al.(2021) report a value of 1.3 kWh/kg for cup production from cardboard. Ligthart(2007) assumes cutting losses of 21%, Cottafava et al. (2021) of 8%, Martin et al. (2018) neglect these.

Since the cups are mainly made from fresh fibers, it is difficult to specify meaningful consumption values and circularity rates. For simplicity's sake, the value **of 7.8 L/kg** derived in chapter 4.4.1 is used for the **freshwater requirement** for cup production; for final energy, the corresponding value plus the energy

²⁴ The analysis by Schill 2025 showed only a small amount of disposable paper cups in LWP waste. Usually, about a quarter to a third of paper and cardboard packaging waste is collected separately (blue system). An estimate of 50% losses is therefore uncertain, but conservative.

consumption for production according to Cottafava et al. (2021), resulting in **2.55 kWh/kg**. Both values were applied to the usable volume assuming average losses of 15% and using the conversion factor from chapter 4.2.2, the values can be found in Table 8.

Table 8: Consumption values and circularity in the recirculating of single-use cups made of paper and cardboard

Size	Value
Freshwater consumption [L/L]	0.27
Final energy demand [kWh/L]	0.101
Maximum circularity (including downcycling)	17
Minimum circularity (requirement for food contact as a result of recirculating)	0

4.4.3 Single-use boxes made of cardboard

FEFCO (2024) has determined the energy requirements and freshwater consumption for a typical (average) corrugated cardboard box based on the market shares of the paper types listed in Table 7. The combination of cardboard types and the production of the box, including the associated material losses, are taken into account. The freshwater requirement also takes into account fresh fiber production, which is why the values extrapolated in chapter 4.4.1 were used to calculate the freshwater requirement caused by recirculating. The value of **2.1 kWh/kg** specified by FEFCO is used for the **final energy requirement**, as it also takes into account the production of composite cardboard and cardboard. Since the low fresh fiber content included in the FEFCO data set tends to reduce energy requirements, this estimate is conservative. The conversion factors from chapter 4.2.2 were used to convert to the usable volume.

After deducting pre-consumer waste and rejects caused by wastepaper, the **proportion of recycled fibers in** the finished cardboard is **82.8%**. This high value can only be achieved if wastepaper from other applications is used. Furthermore, it is not possible to determine whether this is true circularity in the sense that the recycled materials contain identical proportions of the different paper types as the primary product. It is more likely that lower-quality fiber grades, such as corrugated medium and testliner, are preferentially removed, resulting in cascade use (Die Papierindustrie 2025). Based on data from Die Papierindustrie e.V. (Association of the German Paper Industry) (2025), it is possible to estimate the proportion of wastepaper from cardboard and paperboard for various types of packaging at approximately 35 to 80% of the total amount of wastepaper used.

Castellani et al. (2022) examine the life cycle assessment of the production of cardboard for fruit and vegetables, which consists of 53% kraftliner and 47% semi-chemical fluting. Using the above values for the recycled content, the effective recycled content (minus pre-consumer recycled material and rejects) for

the fruit/vegetable box is approximately 17.0%. They do not break down direct energy and water consumption. In an older study for Italy, Levi et al. (2011) assumed a similar composition (60% kraftliner, 40% semi-chemical fluting) for the production of an fruit and vegetable box. They also do not provide detailed figures for energy and freshwater consumption, reporting only a low value of 0.025 kWh for the production of cardboard boxes (which contrasts sharply with the value reported by Cottafava et al. (2021) for the production of cups (1.3 kg/kWh)).

Rasines et al. (2024) determine a Circularity Index (CI) that takes into account not only the proportion of recycled material but also the energy required for recirculating compared to primary production. The authors also conclude that circularity tends to be low.

Table 9 shows the consumption values and circularity of single-use boxes made of cardboard, whereby the freshwater consumption for kraftliner (Table 7) and the final energy requirement of 2.1 kWh/kg specified by FEFCO are allocated to the packaged volume.

Table 9: Consumption values and circularity in the recirculating of single-use boxes made of cardboard

Criterion	Value
Freshwater consumption [L/L]	0.15
Final energy demand [kWh/L]	0.040
Maximum circularity (FEFCO 2024)	82.8
Typical circularity for higher mechanical requirements (Castellani et al. 2022)	17.1
Minimum circularity in cases of insufficient recyclability due to plastic content or exceeding limits for food contact	0

4.5 Circularity in the reusable cycle

4.5.1 Generic consideration of the reusable cycle

Reusable systems **are cleaned in various ways**. There are pool service providers who supply the packaging and take care of professional cleaning. There are companies that take back contaminated packaging directly from customers and clean it, and there are also cases where the customer owns and cleans the packaging. In many cases, cleaning is not necessary after every use (e.g., fruit and vegetable crates). In other cases, multiple cleaning may occur, e.g., in the to-go sector by customers and restaurateurs. Reliable figures on the frequency of cleaning per use are not available.²⁵

²⁵ Disposable packaging is also occasionally rinsed. Whether and when LWP packaging, for example, should be rinsed is therefore the subject of ongoing consumer education.

Depending on **the washing system (centralized vs. decentralized), different dishwashers** or washing systems **are** used to clean reusable packaging.. Table 10 provides an overview of the machine types, their areas of application, and the cleaning methods used.

Table 10: Overview of the types of machines used for reusable packaging and their areas of application

Machine type	Items to be washed	Area of application	Process	Duration of washing cycle [min]	Temperature [°C]	Detergent, additives
Continuous cleaning system	Transport boxes, technical parts	Industry, rinsing centers	Chemical-thermal, surface treatment using water pressure, continuous filling via roller conveyor or similar	< 10	From cold to 80	Alkaline cleaner, no defoamer
Conveyor dishwasher	Homogeneous items, cutlery, plates, cups, etc.	Washing centers	Chemical-thermal (thermal disinfection), continuous filling on conveyor belt	< 10	Up to 85	Alkaline cleaner, rinse aid (acidic), defoamer and drying aids if necessary
Tunnel or basket dishwasher	Heterogeneous items, cups, boxes, trays	Washing centers	Chemical-thermal (thermal disinfection), continuous filling in baskets or racks	< 10	Up to 85	Alkaline cleaner, rinse aid (acidic), defoamer and drying aids if necessary
Hood type dishwasher	Heterogeneous items, cups, boxes, bowls	Decentralized in restaurants, canteens	Chemical-thermal (thermal disinfection), batch filling	< 10	Up to 85	Alkaline cleaner, rinse aid, softener if necessary
Under-counter dishwasher	Heterogeneous items, cups, boxes, bowls	Decentralized in small catering establishments, cafés	Chemical-thermal (thermal disinfection)	< 10	Up to 85	Alkaline cleaner, rinse aid, softener if necessary
Domestic dishwashers	Household dishes including reusable packaging (BYO systems)	Decentralized at the end consumer	Chemical-thermal or enzymatic (at low temperatures), batch filling	60-180	Up to 70	Alkaline or enzymatic cleaner (for low temperatures), rinse aid

Continuous cleaning systems are special conveyor belt systems optimized for a specific type of item to be washed, usually with several lines, which are used in an industrial context. They are used to achieve technical cleanliness, i.e., to remove oil and dust, for example, but can also be used for food boxes, e.g., for fruit and vegetables. The systems are usually multi-stage. A pre-wash for soaking labels and removing proteins is followed by a main wash and rinse. The items to be washed are often fed automatically directly from transport pallets, aligned, and unfolded in the case of foldable packaging. Large systems usually have spin dryers, which reduce surface moisture very energy-efficiently at high speeds.

Manufacturer-standardized conveyor and **basket dishwashers** have a modular design that includes the following elements: machine inlet, pre-wash and main wash zones, rinse zone, drying zone, and machine outlet or outlet table. In highly automated systems, additional steps are carried out upstream and downstream, such as depalletizing, destacking, and sorting before cleaning

and, if necessary, quality control using automatic sensors instead of visual inspection. While **conveyor dishwashers** are usually suitable for homogeneous items and are sometimes specialized for individual types of packaging (e.g., cups with finger bands or extra-flat systems for cutlery), tunnel or basket dishwashers are more flexible and can wash heterogeneous items together. Figure 16 shows a systematic representation of a standard conveyor dishwasher from MEIKO with the five zones described above.

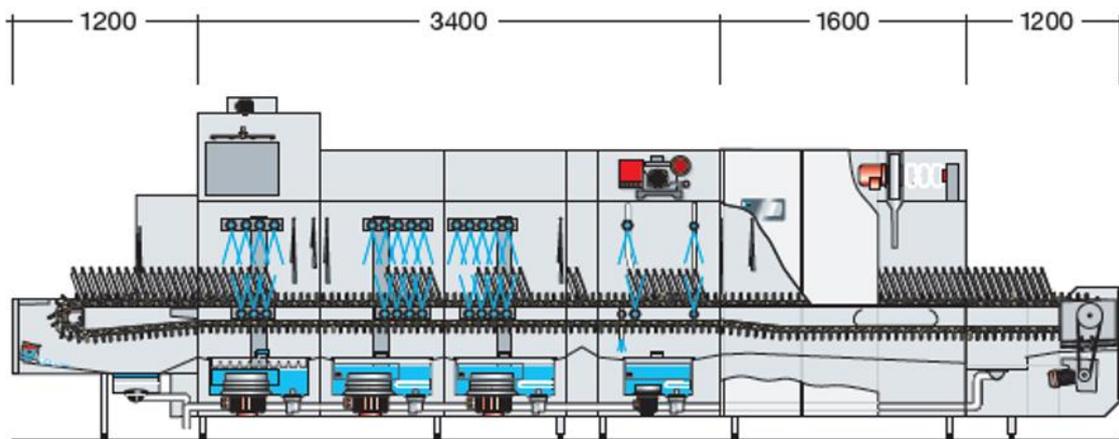


Figure 16: Medium-sized conveyor dishwasher for use in dishwashing centers (MiQ-L model from MEIKO)

Thanks to the modular design, several elements of the pre-wash and main wash zones can be connected in series in a variable manner to achieve a longer dwell time and better cleaning, or to increase the conveyor speed and throughput. In addition, the system can be adapted to the type and material of the items being washed. For example, some systems are specially designed for plastic items. Since **plastic** is significantly more difficult to dry **due to its low heat capacity**²⁶, these systems have **drying zones** with vibration systems and downstream cooling units to prevent condensation on the clean packaging and prevent mold.

Hood and under-counter dishwashers are filled in batches and used for decentralized cleaning, e.g., in the catering industry. **Fehler! Verweisquelle konnte nicht gefunden werden.** Figure 17 shows a hood dishwasher for large throughput heights, which is particularly suitable for bulky items such as boxes.

²⁶ The low heat capacity means that the items being washed cool down quickly after the end of the wash cycle and the heat stored in them is not sufficient for drying. This effect can also be observed in domestic dishwashers.



Figure 17: Hood type dishwasher for decentralized use, e.g., in the catering industry (Model MEIKO M-iClean HL)

Table 10 also provides an overview of the operating parameters of the individual dishwashers and the standards according to which cleaning is carried out. For comparison, see also the overview of regulations and standards in chapter 2. While continuous cleaning systems also clean mechanically using high water pressure and can therefore operate at comparatively low temperatures, cleaning in the other dishwashers presented here is mainly based on chemical-thermal cleaning processes. **DIN EN 17735 recommends heating parts that come into contact with food in a commercial context to over 80°C, which corresponds to thermal disinfection.** For thermal disinfection, there is a correlation between temperature and time.²⁷ In certain applications, e.g., fruit and vegetable crates or crates for technical parts, thermal disinfection can be completely or partially dispensed with. In an industrial context, especially for conveyor belt washing machines, the use of enzymatic cleaning agents is being discussed, which would allow significantly lower operating temperatures of 30 to 40 °C and thus offer high energy-saving potential (Bertling et al. 30.01.2025). Since cleaning systems are very specific to the respective packaging system, the following does not provide mass-related consumption data as is the case with the recirculating of paper and cardboard and plastics, but rather product-specific values.

4.5.2 Reusable plastic cups

Reusable cups can be washed by the end consumer (BYO systems), decentrally at the point of issue (company canteens, restaurants, bakeries, etc.) or centrally in large washing centers (especially at major events). In current practice, the contents of the cups (cold or hot drinks) are irrelevant to the washing process

²⁷ $t = A_0 / 10^{((T-80)/10)}$ with a typical disinfection value $A_0 = 600$ s. This results in a disinfection time of 10 min for 80 °C and 1 min for 90 °C (EN DIN ISO 15883-1).

and the washing system (centralized or decentralized) (Bertling et al. 30.01.2025).²⁸

Cups used in smaller businesses such as restaurants or cafés are usually cleaned locally using hood or under-counter dishwashers. However, smaller outlets can also work with pool service providers who collect cups and wash them centrally in large washing centers using conveyor dishwashers. However, this poses logistical challenges, not only due to the transport routes involved, but also because it is not recommended to store unwashed cups for more than 72 hours in order to prevent mold growth (Hesseler 07.01.2025). This is important because mold can attack the plastic or at least cause irreversible visual damage, rendering the washed items unusable.²⁹ Operators of sports stadiums and concert halls usually have their cups washed centrally by external service providers (e.g., CUP CONCEPT Mehrwegsysteme GmbH or Remondis SE), as large events generate large quantities of wash items in a short period of time.³⁰ However, there are exceptions, such as the Uber Arena in Berlin, where the cups are washed on site (Hesseler 07.01.2025).

Conveyor dishwashers specifically designed for cleaning cups can typically clean up to 8,000 cups per hour per washing line, but in practice this is not achieved due to fluctuating utilization or high levels of soiling. The systems are highly automated and run with fixed operating parameters (temperature, amount of detergent, etc.). Only the conveyor speed is varied and adjusted to the degree of soiling (Bertling et al. 30.01.2025). The type of rinsing system has a significant impact on the process parameters: Water and energy consumption is significantly higher for hood and under-counter rinsers than for conveyor and tunnel rinsers, and even higher when cups are rinsed by the customer (BYO system), sometimes even by hand.

An additional factor that is difficult to quantify, however, is that cups are sometimes cleaned twice: once by the end customer themselves before returning them to prevent contamination during transport, and a second time before filling by the dispensing point. A recent research project by the Birkenfeld Environmental Campus addresses this issue by asking users of the campus's own reusable system to indicate whether the containers have already been rinsed when they are returned (Hartard und Theobald 17.01.2025). No results are available yet (see also footnote ²⁵).

Under normal use and proper storage, a beverage cup can be used approximately 50 to 100 times in practice (Hesseler 07.01.2025). The permissible number of washing cycles is specified as up to 1000 (ReCup 2025). Accordingly, the number of cycles is usually determined not by wash resistance, but rather by mechanical damage during use or by the loss of the washed items. The most

²⁸ However, this is not the case for the washing result, as mold growth and waste, for example, vary significantly depending on the contents; see also section 3.1.

²⁹ However, this effect can also occur when storing disposable packaging made of plastic or cardboard; although the damage to the material is dissipated across the entire flow due to regranulation in the melt or the dissolution process during paper production, it is still present.

³⁰ Between 4,000 (regional soccer league) and 100,000 (first soccer league) cups per soccer game, and up to 200,000 cups during carnival (Bertling et al. 30.01.2025).

common reason for material rejection in washing centers is mold, followed by other contaminants such as lipstick, chewing gum, or damage (e.g., from cigarettes (Hesseler 07.01.2025). Pladerer et al.(2008a) give circulation figures of 60 to 217 for reusable cups used at Bundesliga games, with a weighted average of 107 circulations. Many other studies do not specify a number of circulations but calculate the number of circulations at which a break-even point is reached compared to the single-use system. A realistic value for the circulation of cups is based on the assumption that 15 cycles per year and a service life of 5 years can be achieved, at 75 (Bertling et al. 2022). However, many reusable systems are still in the process of being introduced, meaning that the circulation times for the cups are very long. Our own estimates therefore assume a current circulation rate of only 5, which is used as the lower limit below.

It is problematic when reusable cups are designed specifically for events and are valued by users as collectibles. In these cases, the number of uses can drop dramatically.

Table 11 shows the energy and water requirements for washing cups, which were compiled from the literature and collected during the primary data collection. Several studies that carried out life cycle assessments on the subject without publishing the life cycle inventory data were disregarded, as the consumption data assumed there could not be related to the sub-aspect of cleaning. At the end of the table, two demand values for other to-go food packaging are also shown for comparison. The values vary widely due to the different washing systems.

Table 11: Water and energy requirements for washing cups per unit and wash cycle

Cleaning method	Energy requirements [kWh/cup]	Water requirements [L/cup]	Source
Literature data			
End user, by hand	0.093	0.75	(Martin et al. 2018)
End consumer, by hand	0.109	0.4	(Ligthart 2007)
End consumers, by hand	0.061	0.5	(Cottafava et al. 2021)
End consumer, unclear	0.018	0.2	(Kauertz et al. 2019)
Decentralized, mechanical	0.014	0.14	(Cottafava et al. 2021)
Decentralized, mechanical	0.014	0.10	(Pladerer et al. 2008b)
Decentralized (?), mechanical	0.07	0.7	(Martin et al. 2018)
centralized, mechanical	0.01	0.23	(Cottafava et al. 2021)
central, machine-based	0.018	0.13	(Ligthart 2007)
Primary data			
Central, machine-based	0.008	0.05	Manufacturer specifications
central, machine-generated	0.006	0.03	Manufacturer's specifications
Central, machine-made	0.005	0.03	Manufacturer's specifications
Central, machine-made	0.021	0.07	Primary survey
Central, machine-based	0.014	0.05	Primary survey
Other takeaway packaging for food (trays, boxes)			
Decentralized, mechanical	0.026	0.27	(Gallego-Schmid et al. 2018)
Central, mechanical	0.025	0.34	(Yadav et al. 2024)

The energy consumption of industrial washing systems was approximately three times higher in the primary data collection than the values determined from manufacturer specifications. The discrepancy between these values is not surprising, as in reality the systems are rarely operated at maximum capacity and with optimized process parameters. Added to this is consumption during heating up and self-cleaning of the systems, as well as the rinsing times for the transport boxes for the cups.³¹ Furthermore, the necessary peripherals (cooling, ventilation, etc.) must also be included in the actual energy consumption of the operation. Measurements taken by (Kauertz et al. 2019) study group, which were to serve as the basis for their life cycle assessment comparison, even yielded values seven times higher than the corresponding manufacturer specifications.

For the evaluation, only data from machine cleaning will be used in the following, as it can be assumed that machine cleaning dominates in private households, decentralized in the catering industry, and centrally at pool or cleaning

³¹ Each box takes up about the same space as 50 cups.

service providers. Values **of 0.02 kWh and 0.20 L per cup** currently appear realistic for final energy consumption and freshwater consumption. With optimized operation in large central cleaning facilities and increasing widespread use of the systems, values of 0.01 kWh and 0.07 L per cup are realistic for the future.

Cup cleaning systems usually have one retaining finger per cup. The spacing between these fingers and the operating mode of the system are fixed, so that energy and water consumption is largely independent of cup size. Cups of 0.3 to 0.5 L are usually cleaned. **Most of the data available was for 0.4 L cups.**

Based on the nominal volume, this results in typical values for a 0.4 L cup according to Table 12.

Table 12: Consumption values and circularity in the recirculating of reusable plastic cups

Size	Value (literature, mechanical)	Value (Practice, operation)	Value (Practical, manufacturer's specifications)	Value (literature, manual washing)
Freshwater consumption [L/L]	0.503	0.15	0.093	1.388
Final energy demand [kWh/L]	0.038	0.045	0.016	0.221
Circularity low (due to low coverage)	80	80	80	80
High circularity (for events)	98.7	98.7	98.7	98.7

The values for cups can be easily transferred to other applications that are cleaned in central washing centers (e.g., to-go products in food retail or bowls at fresh food counters (Hesseler 07.01.2025)).

4.5.3 Reusable plastic boxes

Like reusable cups, boxes can be cleaned either locally by the user or centrally in washing centers. There are two types of cleaning and disinfection devices for reusable boxes: the spray system and the immersion bath system with and without ultrasound, whereby a combination of both systems is also possible. The systems can be operated in batches or continuously (DIN 10522). Figure 18 shows a commercially available tunnel washing system for crates from Mimasa Washtech SLU.



Figure 18: Commercially available tunnel washing system for crates (model DA-150-MS, Mimasa)

Continuous systems for crates are designed for capacities ranging from 100 to 9,000 crates per tunnel per hour (MIMASA 2025). Depending on the degree of automation, the systems can include automated equipment such as destackers, stackers, turners, feed and/or collection conveyors, and return conveyors. For large washing centers, highly customized large-scale systems are designed that integrate several lines and washing lines. For example, the IFCO washing center in Voerde has three washing lines, each with three lines, and cleans a total of up to 500,000 crates per day or approximately 100 million crates per year (IFCO 2025). Each item to be washed automatically passes through the following stations in the plant: depalletizing, destacking, presorting, and opening. It is then pre-rinsed in two parallel washing tunnels, cleaned and disinfected, and rinsed with freshwater. The subsequent folding, sorting, drying, stacking, palletizing, and strapping are also carried out by machine (Schaich 29.01.2025).

Table 13 shows the requirements for cleaning boxes identified in the literature and collected during the study. It should also be noted here that there are a number of other life cycle assessment studies that compare single-use and reusable crates without disclosing the assumed consumption for the individual process steps (such as cleaning or recirculating), which made them unusable for this comparative study. Nevertheless, the data situation here is better than for the single-use systems compared, where consumption is fully integrated into life cycle assessment data sets.

Basically, it can be seen that energy and water consumption are dominated by the degree of contamination and the capacity of the plant. High values are particularly typical for small plants that are not optimized for crate cleaning and for cleaning difficult goods (e.g., boxes for transporting

meat and fish). Industrial facilities that are optimized for specific types of packaging and goods that are considered less critical, on the other hand, achieve significantly lower values.

Rasines et al. (2024) report number of circulations for boxes of 140, Levi et al. (2011) do not specify a figure, but instead conduct a break-even analysis. Abejón et al. (2020) assume 10 to 15 uses per year over a useful life of 10 years. Ceballos-Santos et al. (2024) are significantly more optimistic and assume 120 cycles per year with a service life of 10.5 years (!), but at the same time cite a replacement requirement of 1% without referring to a specific period. For further evaluation, a conservative **circulation figure of 200 is used for simple flushing tasks and 100 for more difficult ones.**

Table 13: Water and energy requirements for washing boxes per unit and washing process

Cleaning method	Dishwasher type, Application	Energy requirement [kWh/box]	Water consumption [L/box]	Volume [L]	Source
Literature data					
Decentralized	Unknown, fruit/vegetable boxes	0.036	0.10	43.2	(Levi et al. 2011)
Decentralized	Medium Industrial plant, fish boxes	0.290	1.2	20	(Ceballos-Santos et al. 2024)
Central	Industrial plant, fruit/vegetable boxes	0.049	0.19	36	(Rasines et al. 2024)
unclear	unknown	0.447	0.50	34.2	(Abejón et al. 2020)
Primary data					
Central	Standard plant, n. d.	0.413	1.29	48.0	Primary survey
Central	Standard investment, n.a.	0.239	1.18	48	Primary survey
Central	Standard system, technical flushing material,	0.270	0.06	24.6	Primary survey
Central	Small standard system, not optimized for crates	1.212	1.16	76.0	Primary survey
Central	Industrial plant, fruit/vegetable boxes	0.065	0.19	30.0	Primary survey
Decentralized	Medium Industrial plant, meat boxes	0.278	1.22	35	Primary survey

For the evaluation, a distinction is made between simple and difficult items to wash, suitable values are determined, related to the nominal volume specified in the table above, and combined with conservative and optimistic circularity. Based on the nominal volume, **typical values** are obtained **according to** Table 14.

Table 14: Consumption values and circularity in the recirculating of reusable plastic boxes

Criterion	Value (difficult rinsing task)	Value (simple rinsing task)
Freshwater consumption [L/L]	0.0369	0.0063
Final energy demand [kWh/L]	0.0091	0.0022
Circularity	99	99.5

5 Comparison of water and energy consumption and circularity of the two options for closing the energy and water cycle

The following section summarizes, compares, and discusses the energy and water consumption of the two system variants determined in the chapter 4

5.1 Tabular overview

The following Table 15 provides an overview of all the data collected. Individual aspects are addressed and illustrated in the following chapters using graphs. The term »relative loss« refers to the proportion that does not circulate, corrected for material efficiency (see chapter 4.2.2).

Table 15: Overview of the data collected for final energy, freshwater, circularity, and relative loss

Circular system (material, application)	Final energy per volume [kWh/L]	Freshwater per volume [L/L]	Circularity [%]	Relative loss [%]
BOX				
MW (KS, difficult flushing task)	0.009	0.037	99.0	3.0
MW (KS, light flushing task)	0.002	0.006	99.5	1.5
EW (Cardboard, downcycling)	0.040	0.15	82.8	17.2
EW (cardboard, food, mechanically demanding)			17.1	82.9
EW (cardboard, FCM)			0.0	100.0
CUP				
MW (literature, manual washing)	0.221	1.388	N/A	N/A
MW (Practice, operation, low coverage)	0.045	0.15	80	60
MW (Practice, operation, low event)			98.7	3.9
MW (literature, industrial, low coverage)	0.038	0.503	80	60
MW (literature, industrial, event)			98.7	3.9
MW (manufacturer's specifications)	0.016	0.093	N/A	N/A
EW (KS, downcycling)	0.086	0.023	23.2	76.8
EW (KS, FCM)			0.0	100.0
EW (cardboard, downcycling)	0.101	0.270	17.0	83.0
EW , mechanical (cardboard, FCM)			0.0	100.0

5.2 Comparison of single-use boxes made of cardboard with reusable plastic boxes

Figure 19 shows the final energy demand and freshwater consumption for the various box options. The literature data for rinsing reusable boxes was confirmed in the primary survey and is therefore not shown separately. Consumption was compared with data from FEFCO and supplementary literature data for cardboard boxes.

Basically, it was found that cleaning **reusable boxes** per use requires much less final energy and freshwater than the competing recirculating of cardboard boxes. The extent of this effect depends largely on the cleaning task. While slightly soiled **reusable boxes**, e.g., for transporting fruit or vegetables, consume **only about 1/20** (0.002 kWh/L packaging volume) of **the energy** and **1/25** (0.006 L/L packaging volume) of **the consumption of the recirculating process for wastepaper to cardboard**, even heavily soiled reusable crates, e.g. **for meat and fish, still require less than 1/5 of the energy and freshwater** (0.009 kWh/L and 0.037 L/L packaging volume, respectively). It should be noted that some packaging tasks cannot be performed at all in single-use boxes made of cardboard without coating or inliner.

The data on consumption at cleaning facilities for reusable packaging clearly shows that large industrial facilities can be operated much more efficiently (see chapter 4.5.3). Since both systems, boxes made from cardboard and reusable plastic, are technically advanced, the clear advantage of reusable boxes may also point to opportunities for other reusable systems that are currently still operating as niche products.

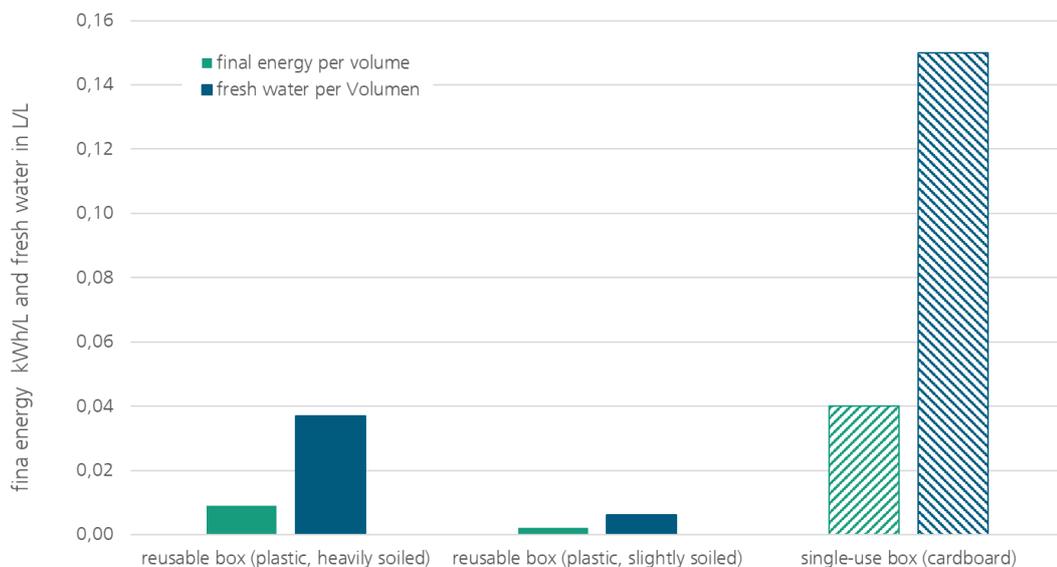


Figure 19: Energy and water consumption of single-use and reusable boxes. In addition to data from literature, primary data (PD) was also collected for the reusable boxes.

5.3 Comparison of single-use beverage cups made of cardboard or PP with reusable plastic beverage cups

Figure 20 shows the final energy consumption and freshwater consumption for cups. Three consumption groups were formed for reusable systems. The first column group reflects actual practice, which was determined by collecting primary data at industrial facilities. Compared to the literature data (second column group), less than a third of the freshwater is required in industrial reusable practice, whereas the final energy requirement is slightly higher. This is likely due to the fact that industrial plant capacity is currently often underutilized. Manufacturers (third column group) show significantly lower final energy consumption values. The challenge for the future is to tap into this potential, e.g., through optimized utilization.

When comparing reusable cups with single-use cups made of plastic or cardboard, it is noticeable that both single-use systems require significantly more final energy to close the cycle (0.1 and 0.09 kWh/L, respectively). The two single-use systems hardly differ in this respect. However, they differ in terms of freshwater requirements: plastic recirculating manages to get by with the lowest amounts of freshwater – but at the expense of low circularity (for the interrelationship with circularity, see the following chapter). In addition, the two consumption values for manual washing are shown in red in the diagram. These are significantly higher than all other values. Pre-cleaning or double cleaning would increase the total value even further and should be avoided in both systems if possible.³²

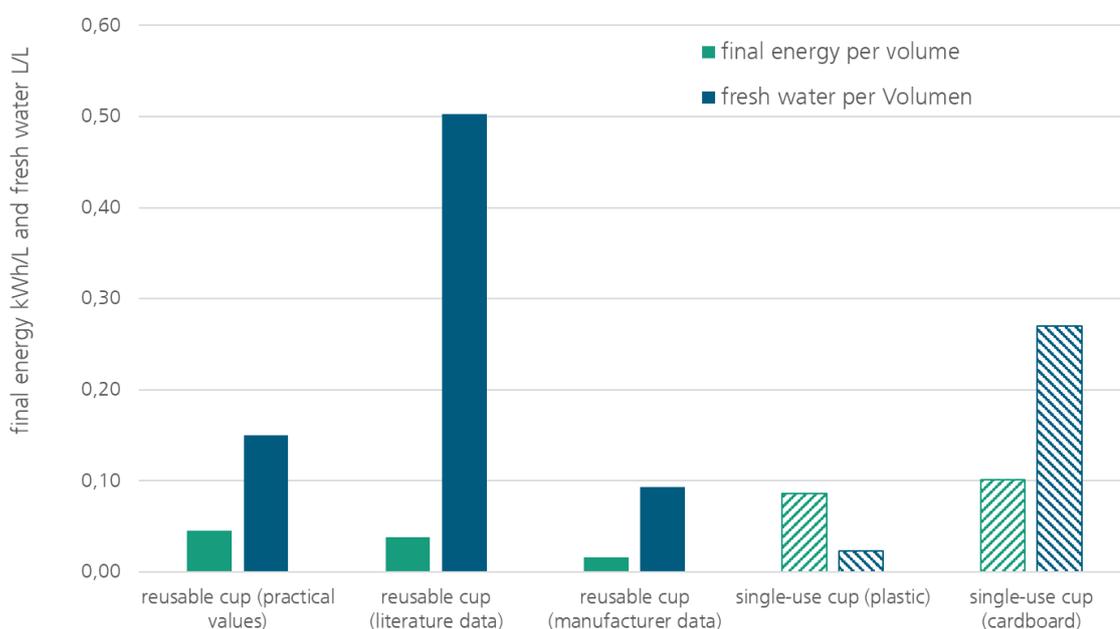


Figure 20: Energy and water consumption of single-use and reusable cups. In addition to literature data, primary data was also collected for reusable cups.

³² It is not uncommon for consumers to rinse disposable LWP packaging or reusable packaging before disposal in order to remove food residues and prevent mold.

5.4 Energy and water consumption taking into account the circularity achieved

As shown in Chapter 4, **single-use systems** achieve only a very **low level of circularity**. It therefore seems sensible to include this aspect in the assessment. Since freshwater and final energy are formulated as consumption variables, it seems sensible to use the **loss** $_{\text{loss}_{\text{ges}}}$ instead of circularity $_{\text{ges}}$, as minimizing all three variables is then ecologically advantageous. As expected, reusable packaging tends to show lower losses. However, in order to make a fair comparison, it should be taken into account that more material is lost with each piece of reusable packaging that is lost. If we take the **mass ratio** $m_{\text{EW}}/m_{\text{MW}}$ of reusable to single-use packaging of 2.7 for boxes and 2.8 for cups, as determined in chapter 4.2.2, the losses of the reusable systems increase accordingly. A so-called relative loss $_{\text{rel,MW}}$ can be defined that takes this into account.

$$\text{loss}_{\text{rel,MW}} = m_{\text{MW}}/m_{\text{EW}} \times (1 - \epsilon_{\text{MW}}) \quad (6)$$

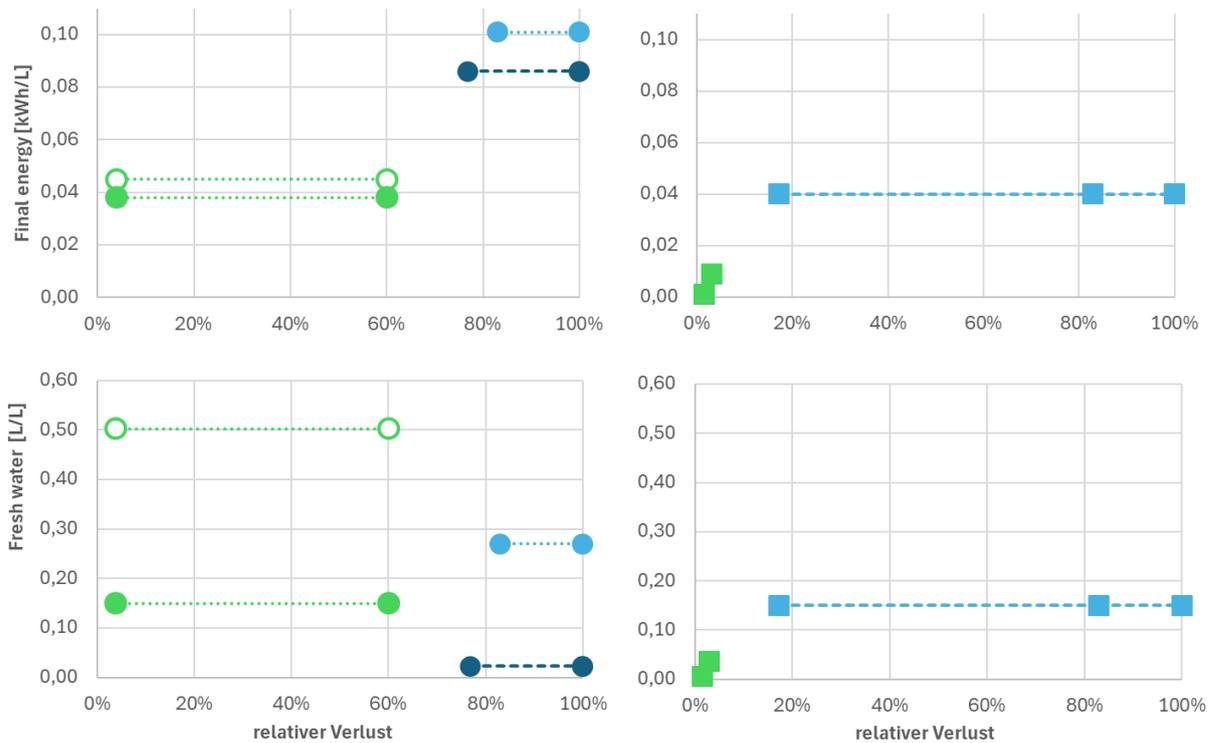


Figure 21 illustrates this relationship. The final energy requirements and fresh-water consumption for cups and boxes are plotted against the relative losses.

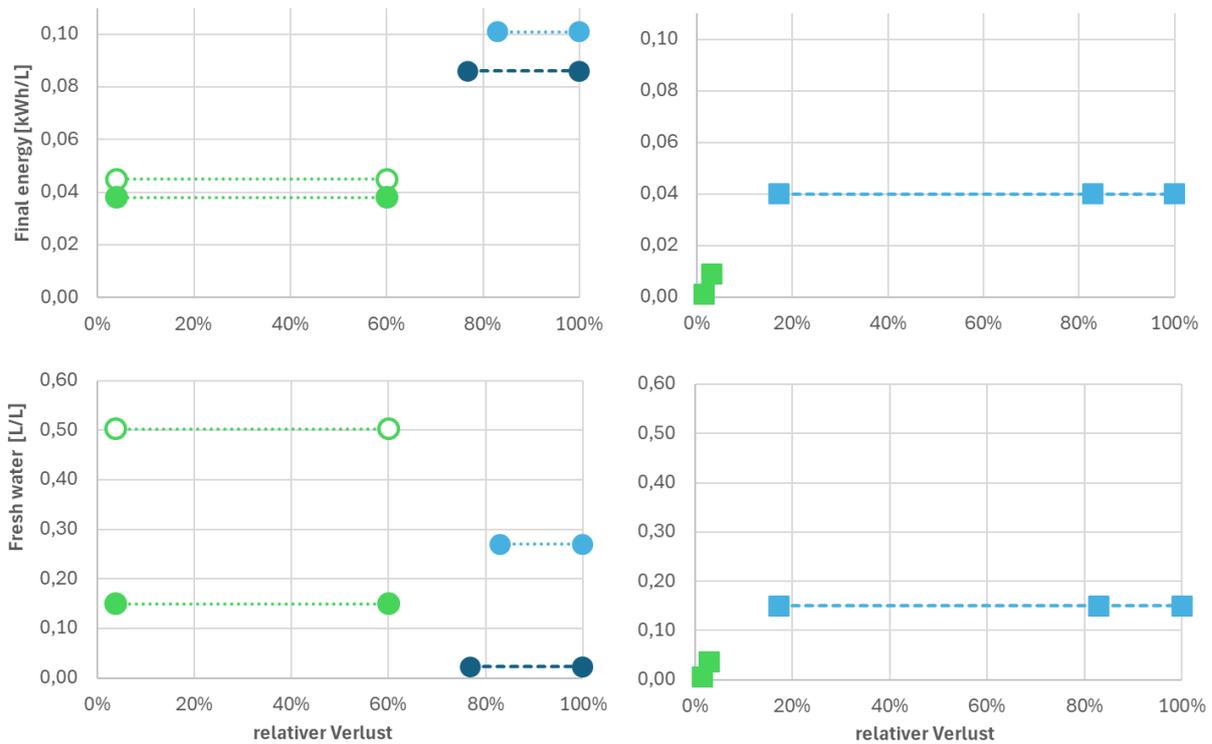


Figure 21: Final energy demand (top row) and freshwater consumption (bottom row) via the relative loss for cups (left column, circles) and boxes (right column, squares). Reusable (green; literature data unfilled, own data collection filled), single-use cardboard (light blue), single-use plastic (dark blue)

For single-use cups (left column), two values were plotted for the loss: 100% if food contact is specified as the recirculating target, and 77% or 82% if downcycling is accepted. For reusable cups, the value collected in this study (green, filled) and the older literature value (green, unfilled) are plotted. The loss range corresponds, on the one hand, to values that are achieved today, for example at events, and, on the other hand, to values that are currently realistic for to-go cups in open systems. The graphs show that reusable cups perform better, especially after data collection. Single-use systems have high material losses and high consumption at the same time; the only exception is freshwater consumption for single-use plastic cups, which is lower than for competing reusable alternatives. Nevertheless, reusable systems must aim to further reduce losses. The advantages only remain if the number of circulations significantly exceeds 5 (corresponding to a relative loss of 60% in the diagram) and if industrial washing systems are operated efficiently and at high capacity in terms of water consumption.

In the case of boxes, the reusable plastic box is compared with a single-use cardboard box. The two reusable points (green) are the easy and difficult washing tasks (fruit/vegetables and meat/fish). Three loss levels are distinguished for paper boxes: 100% if food contact cannot be achieved; 83% if only a recycled content of 17% is possible due to mechanically demanding packaging tasks, as is the case with combinations of kraftliner and semi-chemical fluting, e.g., in

fruit and vegetable cartons, and 17% if downcycling is permitted for less demanding tasks (e.g., a corrugated cardboard box for applications without food contact). In the case of boxes, the final energy consumption and freshwater consumption show that, despite the higher consumption of cardboard, the losses are also significantly higher. This still applies even if the lowest loss rate is assumed – i.e., including downcycling applications.

In the case of single-use systems, it is to be expected that the reduction in losses and increase in circularity that is being sought and will be necessary **in the future** can only be achieved through increasingly complex and costly separation and cleaning technology. This suggests that energy consumption and freshwater consumption will continue to rise. The data points in the diagrams would shift to the top left. In reusable systems, reducing losses requires upscaling the systems, which should improve utilization in the cleaning facilities and increase the potential for automation. For operators, investments in improved cleaning technology would then be worthwhile. Both should reduce freshwater and final energy consumption. The data points would therefore tend to shift further to the bottom left.

5.5 Comparison of the study results for reusable cups and boxes

Figure 22 shows the energy and water consumption of reusable boxes (first and second column groups) and reusable cups (third and fourth column groups). The consumption values for the cups are significantly higher than for lightly soiled boxes (x 45) and even for heavily soiled boxes (x 4). As the calculation of specific material costs (mass per filling volume) in Chapter 6.1 shows, only part of this additional consumption can be explained by the increased use of material in relation to the filling volume (approximately 1.8). The manufacturers of cup cleaning systems specify lower values that could be achieved by increasing efficiency through adjustments to the operating mode (capacity utilization) (x 2.8 for energy and x 1.6 for freshwater). However, there remains a gap between these values and the consumption values for boxes. This could be explained in part by the type of contamination, which is also the cause of the higher consumption data for reusable crates for meat and fish. However, this alone is unlikely to be a sufficient explanation for drinking cups, which are usually used for water-soluble beverages. It can therefore be concluded that there is significant potential for optimization, particularly in terms of scaling and maturity of the technology compared to boxes.

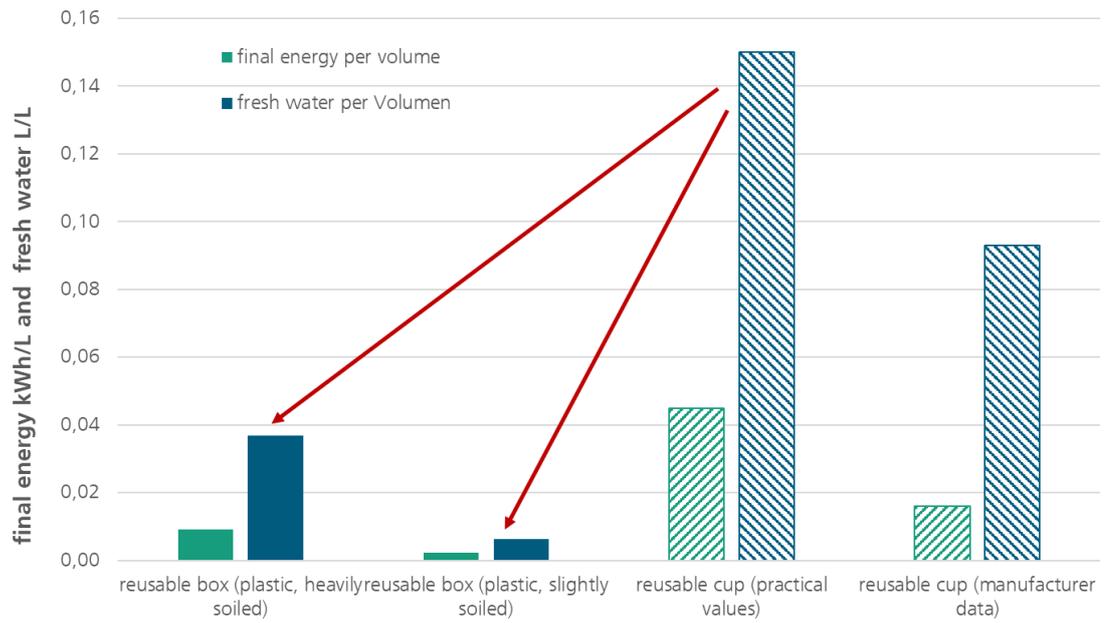


Figure 22: Comparison of energy and water consumption for reusable cups and boxes

6 Conclusion and recommendations

6.1 About the study

It is largely undisputed that reusable packaging, especially once certain minimum number of circulations has been reached, is preferable to single-use packaging in terms of resource consumption. Criticism of reusable systems focuses mainly on transport logistics and water and energy consumption during the cleaning process. The present analysis shows that this criticism is not justified, at least in terms of energy and water consumption. Transport costs are highly dependent on the prevalence of the system and the stackability, nestability, and compactability of the packaging systems and should be examined in more detail in a separate study.

In the single-use system, the cycle is closed by recycling, while in the reusable system it is closed by cleaning and reuse. This means that with reusable systems, not only the material but also the product form is retained, which can reduce energy and resource consumption. The competition between the two systems can be described as **material retention vs. form retention**.

This report focuses on direct consumption in closing the cycle – through washing (reusable) or sorting, processing, and reshaping (single-use). **Direct energy and water consumption** form an essential basis for life cycle inventory analyses in life cycle assessment studies and for the technical optimization of processes. The values are easier to interpret and understand than the aggregated impact categories of life cycle assessments. Therefore, this study is **not a life cycle assessment** and cannot replace one. It does not take into account all life cycle phases, transport, or material production in full. For this reason, no general ecological advantages for single-use or reusable products can be derived. Rather, the aim is to gain a deeper understanding of the energy and water consumption of the two systems.

The selection of **the demonstrators: to-go cups** and **boxes/crates** was made jointly with the client (Stiftung Initiative Mehrweg) and was based on their practical relevance: to-go cups represent large and visible amounts of waste in public spaces; boxes/crates represent high-volume transport packaging in the B2B sector with significant logistical relevance. The selection of these packaging types allows for a representative analysis of recirculating in two different usage contexts (end consumers vs. logistics).

Fundamentally, the study showed that the data available on energy and water consumption for both single-use and reusable packaging is very poor. Material and process data are largely unspecific. Primary data collection has improved the situation somewhat, at least for reusable packaging. Nevertheless, many life cycle assessment studies repeatedly refer to outdated data or industry data that is not very representative for specific tasks. The lack of availability and visibility of specific operating data creates little incentive for concrete improvements at the process and product level.

Recommendations

- *Regular collection of life cycle inventory data for single-use and reusable systems and a breakdown of end-of-life mass flows in relation to actual utilization rates would be helpful in enabling a fair assessment. The relevant data should be published as part of ongoing monitoring, for example in the form of a »Circular Packaging Radar«, in order to intensify competition for the best circular strategy.*

6.2 The legal situation of single-use and reusable packaging

Plastic packaging is particularly heavily regulated compared to other materials. There are numerous requirements, especially for packaging made from recycled plastic that comes into contact with food. EU Regulation 2022/1616 regulates in detail the conditions under which recycled plastics may be used in food packaging. Currently, **only two recirculating processes are approved throughout the EU**: the mechanical recirculating of PET from post-consumer waste and the recirculating of production waste from closed cycles. For all other technologies and types of plastic, there is a lengthy approval process that can take several years. This leads to considerable **legal uncertainty and inhibits investment**. This is a disadvantage for reusable packaging, which in the category of small load carriers (represented here by boxes) is made exclusively from plastic.

The **tension** between the political goal of reaching a Circular Economy and the requirements for food contact is complex. The **PPWR** calls for increasing recycled content quotas for plastic food packaging from 2030 onwards. At the same time, recycled materials may only be used if they comply with very strict food contact requirements – which is rarely feasible in practice. This **means that the circularity of single-use packaging remains virtually impossible at present**, as there are no suitable, legally secure recirculating pathways. However, these regulations also apply to reusable packaging if it is manufactured after 2030. This is particularly problematic as the service life of reusable packaging is usually between 5 and 20 years, meaning that there is unlikely to be enough recycled material available on the market.

Paper, cardboard, and paperboard (**paper and cardboard**) pose another regulatory problem. The BfR excludes the use of paper and cardboard from **mixed packaging collections** (e.g., LWP – yellow bag) for food packaging, as critical substances cannot be reliably excluded. However, it is practically impossible to prove that packaging does not originate from such sources. Conversely, the use of **recycled paper and cardboard from the blue bin** (pure wastepaper) is permitted under certain conditions, in particular material requirements. In practice, however, **cardboard beverage cups are often sorted out** in paper mills because coatings or contaminants are problematic. A closed paper and cardboard cycle is therefore usually not available.

Unlike single-use packaging, **reusable packaging is subject to detailed standards governing** its use, particularly cleaning. There are clear regulations – e.g., DIN 10522 and DIN EN 17735 – on hygiene, cleaning effectiveness, and

requirements for cleaning procedures and test intervals. These standards ensure hygienic reuse and are also subject to external control (e.g., by veterinary offices).

Another problem is that the PPWR prescribes material-related **reusable quotas**, from which **cardboard is explicitly excluded**. This creates a regulatory incentive to substitute plastic with cardboard and to circumvent the politically desired increase in the proportion of reusable packaging. At the same time, the high **recyclate requirements also apply to reusable plastic systems**, which makes their use even more difficult.

Overall, it is clear that the regulatory framework does **not** provide **a consistent system** for promoting genuine recirculating. Closed-loop recirculating is currently hardly feasible, especially for single-use packaging, regardless of the material.

Recommendations

- *The implementation of the individual measure for cardboard possible in (EG 1935/2004), i.e., a specific regulation for food packaging made of paper and cardboard, should be considered. Plastic-coated paper and cardboard must be subject to special requirements, as they are a potential source of microplastics and are difficult to recycle.*
- *The BfR recommendations and the CEPI guidelines based on them regarding which types of wastepaper are suitable for food contact are vague and can be interpreted in different ways. Suitable types according to DIN EN 643 are not mentioned. A clearer statement could give industry and consumers more certainty.*
- *The report announced by the Commission in the PPWR and due on December 31, 2026, on the presence of substances of concern in packaging and packaging components should address paper and cardboard and plastic packaging equally.*
- *The exclusion of paper and cardboard packaging from the reusable quota in the PPWR may lead to a shift from single-use plastics to single-use paper and cardboard. The results of this study show that this would be a misguided development, particularly for the B2B packaging of crates, boxes, barrels, etc., which are explicitly mentioned in Article 29 PPWR. A more intelligent regulatory approach needs to be developed here.*

6.3 Contamination and decontamination in the packaging cycle

For successful cleaning, **the chemistry, mechanics, temperature, and time** of the process must be coordinated (Sinner's circle) in order to achieve hygienically perfect results. Water plays a central role in heat transfer and the removal of dissolved substances. The interaction of temperature and time is relevant for thermal disinfection.

The cleaning of packaging or packaging materials in the cycle is relevant in both reusable and single-use systems. After use, reusable packaging is often contaminated with **organic residues** such as fats, proteins, and carbohydrates, which can promote microbial growth, such as bacteria and mold. Equally problematic are adhering beverage residues or intense flavors such as coffee or curry, which are difficult to remove. **Chemical components** such as bisphenol A (BPA) in polycarbonate or phthalates as plasticizers can also be released at high washing temperatures.

The processing of **plastic recyclates** from post-consumer waste poses additional challenges. In addition to organic contaminants, foreign substances such as label adhesives, printing inks, metals, and non-homogeneous plastics are often present. In large-scale washing plants, a multi-stage cleaning process is carried out: First, the plastic flakes are intensively washed at temperatures of around 80–90 °C with lye and surfactants, then mechanically treated and rinsed several times. In the subsequent extrusion at 200–280 °C, microorganisms are killed, solids are filtered out, and volatile substances are removed. These steps are necessary to obtain recyclates that are suitable for **food** contact—a goal that can only be achieved with considerable technical effort.

Cleanability depends heavily on the **material properties**. Many plastics are **hydrophobic**, meaning they require special wetting agents. At the same time, some materials, such as PET or PS, show **dimensional distortion** at higher temperatures. Plastics such as polypropylene (PP) or HDPE are therefore particularly suitable for reusable applications as they are resistant to heat and chemicals. This is proven by test procedures in accordance with DIN EN 12875, which simulate up to 125 rinse cycles, for example.

There are also hurdles in **paper recirculating**. In addition to substances inherent in paper, such as coatings and printing inks, **PFAS** and organic residues are also often present. Cleaning is carried out using processes such as deinking, boiling, and multiple washing, often at temperatures above 100 °C. Despite these measures, not all undesirable substances can be completely removed. For this reason, high-quality material recirculating into new food packaging is usually not possible—instead, downcycling into other products often takes place.

Recommendation

- *The specific cleaning properties of plastics should be addressed in research work. Design and material optimizations that facilitate complete drying and reduce susceptibility to scratches would be particularly interesting in this context.*
- *As outlined in the chapter 6.2, the migration of substances from paper and cardboard packaging into food should be examined in greater depth, the achievement of prescribed limit values such as those for PFAS in the PPWR should be checked, and clear instructions for the paper industry on the use of wastepaper should be derived from this, taking into account the goals of food safety and a circular economy in a balanced manner.*

6.4 Processes and facilities for recirculating

The LWP path is essential for the collection and utilization of plastic waste. However, even before the actual **material recirculating process**, approximately 36% of single-use plastic is lost because it ends up as misplaced waste in residual waste or other unsuitable collection systems, is exported, is not returned within the typical time frame, or is littered. Despite complex and innovative process and plant technology, the plastic flow in the LWP path continues to decrease too rapidly through sorting, processing, and regranulation. In the end, only **23.2% of the original plastic quantity** is still available.

In the production of paper and cardboard, savings in consumption and increases in the use of wastepaper seem hardly possible anymore, as these plants have long been optimized. It might be more important to remove pollutants from the entire stream, which would enable utilization in food contact applications in the medium term. However, this would also require the elimination of coatings and barriers that are critical for recirculating, which in turn would limit the range of applications for paper and cardboard. Although higher recirculating rates are achieved in the paper and cardboard cycle, if the quantities recycled domestically are related to domestic consumption, the **circularity of paper and cardboard** reaches **approximately 72%**. This value is achieved or even exceeded if downcycling (in the sense that food contact materials are used for other applications without food contact) is permitted. If food contact is excluded, as required by the BfR recommendation for mixed collected paper and cardboard waste, circularity can drop to zero.

The circularity of **reusable packaging** is significantly higher. However, it should be noted here that in a fair comparison with single-use packaging, due to the mass ratio of approximately 2.7 to 2.8 (reusable/single-use), the loss of reusable packaging is significantly greater and the »relative loss« decreases. Reusable systems with a circularity of less than 80% (corresponding to a circulation factor of 5) therefore lose their ecological advantages.

Recommendation

- *The circularity in the single-use system is currently insufficient in terms of quantity and quality (no food contact). In the expected future attempt to increase this through improved sorting and processing, the development of energy and water consumption should be critically examined. Concrete guidelines would be useful here.*
- *The actual return rates for reusable systems in the B2C sector are partly unknown, partly because customers do not clearly distinguish between pool systems and BYO systems. Customer knowledge needs to be deepened and the clarity of labeling with regard to the system and correct disposal path needs to be improved.*
- *High return rates are essential for a positive assessment of reusable systems. Especially in the case of packaging such as cups, which are handed*

out to end consumers, efforts and creative solutions (e.g., digital recording) are necessary to increase these rates.

6.5 Comparison of energy and water consumption between the systems

The result of the comparison is clear for **boxes**. Significantly less energy and water are required to prepare reusable boxes for return to the cycle – **around 1/40 (1 kWh/m³) of the energy consumption and 1/15 (5 L/m³) of the freshwater** compared to cardboard boxes. At the same time, the circularity of the boxes is over 99%, while cardboard boxes for non-food contact applications achieve a circularity of 83%, which is reduced to 17% due to mechanical requirements and to 0% for food contact applications. Primary data collection on consumption for reusable boxes has confirmed the literature data.

For **cups**, the primary data collection showed a reduction in freshwater consumption of approximately 70% to 0.15 L/L compared to the average values reported in the literature. If only data for machine washing from the literature is included, the values reported there for energy consumption are roughly confirmed. At the same time, however, it is also clear that manual washing is not an ecologically sensible option in either a reusable system or a single-use system (before disposal in the yellow bin). The **reusable cups show significantly lower energy consumption than single-use cups made of cardboard (0.101 kWh/L) and also than single-use plastic cups (0.86 kWh/L). However, the water consumption for plastic cups during recirculating (0.023 L/L) is significantly lower than during cleaning (0.150 kWh/L)**. Reusable cups are superior in terms of circularity. However, considering that circularity losses in reusable packaging are associated with higher mass loss, the current circularity of reusable cups is not yet satisfactory. It must be taken into account, however, that neither the recyclates from paper and cardboard nor plastic single-use cups are reused in food contact applications.

Recommendations

- *The effort required for recirculating in single-use systems is immense. Numerous studies show that reusable systems are clearly superior where they have been able to establish themselves and achieve a certain level of distribution and scale. Regulations should therefore not only specify reusable quotas, but also provide regulatory support for concrete measures to implement and scale reusable packaging systems.*

6.6 Promotion of reusable packaging

The results of this study, which show the superiority of reusable systems in the three key environmental aspects of final energy demand, freshwater consumption, and cycle losses, contradict the market dominance of single-use systems. Even though there may be many economic, systemic, and psychological reasons for this, from a scientific point of view, it makes sense to examine the responsibility of science itself and how **research activities** compare between the two cycle systems. To this end, an investigation was conducted into how many

research projects address recirculating of single-use items and how many deal with aspects of reusable systems. It turns out that there are many hundreds of publicly funded projects in the field of recirculating of single-use items, while the number of projects on reusable systems is in the low double digits (Figure 23).

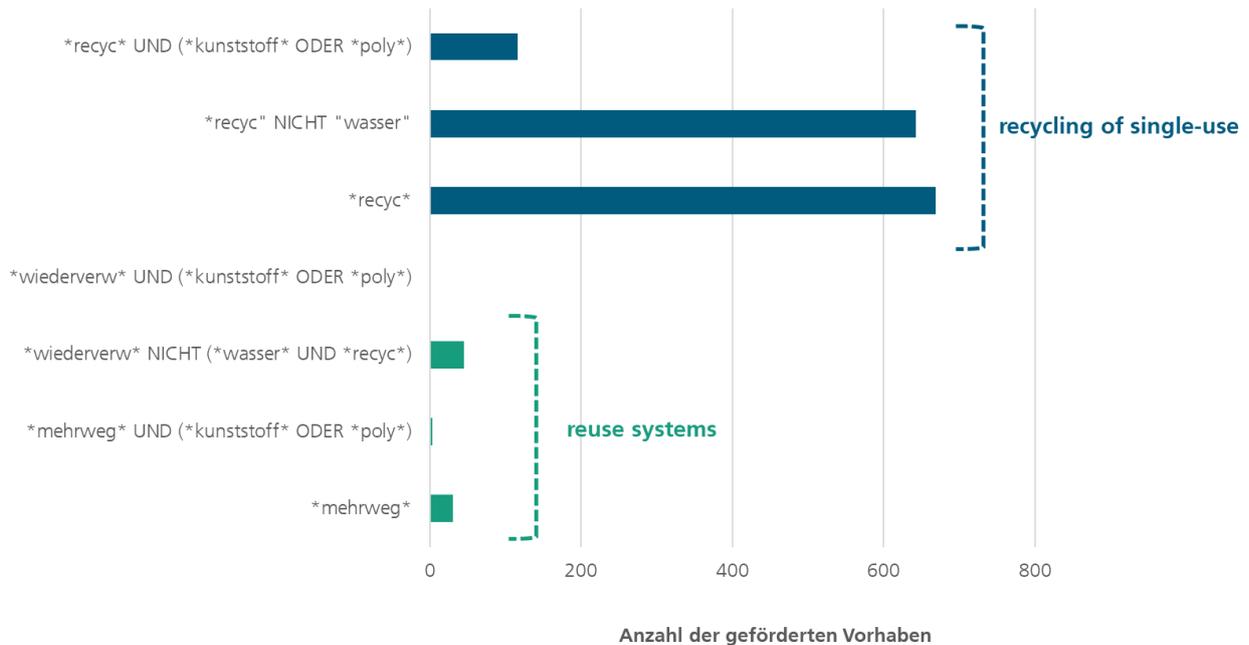


Figure 23: Number of projects funded by the federal government according to keywords in the federal funding catalog, orange: projects related to recirculating, blue: projects related to reusable systems (joint projects are counted according to the number of consortium participants).

Recommendation

- *If reusable systems are to be given greater priority, a change in research agendas and funding priorities is necessary. Aspects of washing technology, return logistics, and material suitability should be addressed.*

7 Appendix A – Glossary

For definitions of the concepts and terms used here, see the Fraunhofer »Glossary on Reuse / Reusable Glossary« at [Glossary Reuse Glossary Reusable](#).

8 Appendix B – Interview partners

To determine energy and water consumption in the cleaning of reusable packaging, interviews were conducted with the following companies:

Table 16: Main interview partners, reusable packaging systems

Company name	Interviewee	Interviewer	Date
GST Worldwide Logistics GmbH	Enrico Plogsties, (Managing Director)	Jürgen Bertling, Jan Blömer	Questions answered in writing by email on November 4/19, 2024
Hammelmann Service GmbH & Co. KG, WBG Pooling GmbH & Co. KG	Jörg Hammelmann (Managing Director) Felix Borgerding (Managing Director)	Jürgen Bertling, Jan Blömer	February 19, 2025
IFCO Systems GmbH	Dirk Schaich, (Director of Supply Chain) Nikolei Kitzberger (Working Student)	Jürgen Bertling, Jan Blömer	January 29, 2025
MEIKO Deutschland GmbH	Ludger Hesseler, (Key Account Manager Reusable)	Lena Bersch, Jürgen Bertling	January 7, 2025
Operator of a cup washing system, anonymous	N.N.	Lena Bersch, Jürgen Bertling, Jan Blömer	January 30, 2025

In addition, in-depth discussions were held with the following companies and institutions:

Table 17: Interview partners for deep dives

Company name	Interview partner	Date	Topic
BfR	Thomas Tietz (Head of Unit Safety Food Contact)	March 13	Use of wastepaper for food applications

bvse	Romy Kölmel	12/19	Recovery of fibers from coated specialty papers, legal requirements Paper recirculating
INEOS Styrolution	Frank Eisenträger	February 25	Recirculating of PS for food applications, legal requirements
HS Pforzheim	Raphael Schill (Research Associate)	01.08.25	Cup proportions in the LWP fraction, packaging study 2024
Birkenfeld Environmental Campus, Trier University of Applied Sciences	Susanne Hartard, Klara Theobald	Jan. 17	Data collection on reusable systems

9 Appendix C – Various calculations

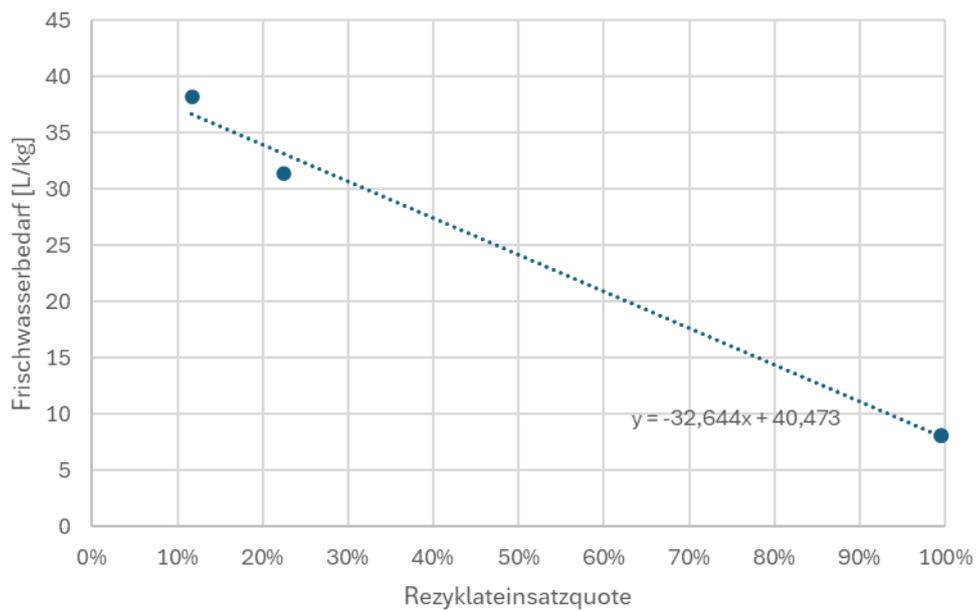


Figure 24: Freshwater requirements for paper and cardboard, linear regression line for extrapolation to 100% recirculating

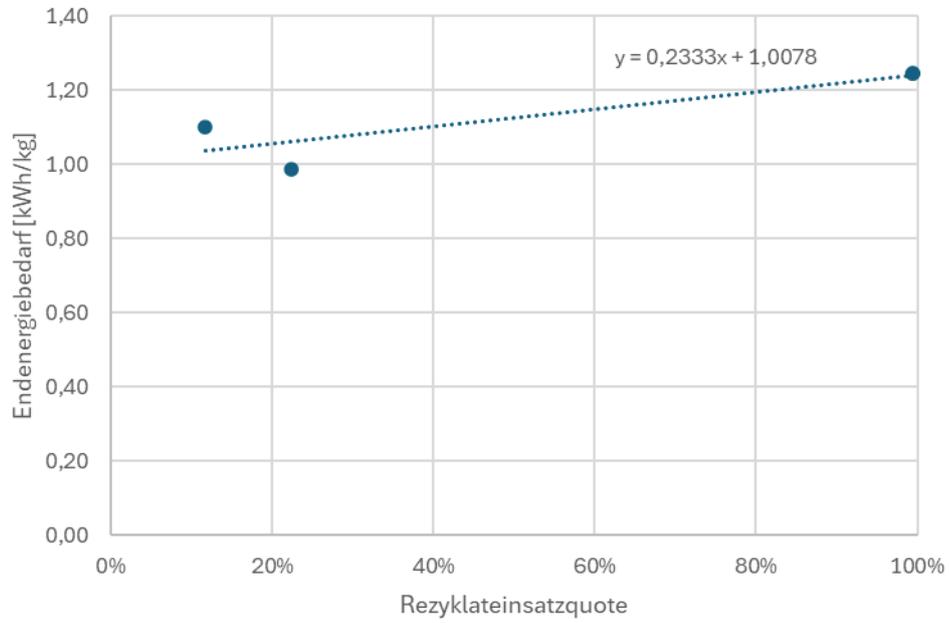


Figure 25: Final energy demand for paper and cardboard, linear regression line for extrapolation to 100% recirculating

10 Literature

Abejón, R.; Bala, A.; Vázquez-Rowe, I.; Aldaco, R.; Fullana-i-Palmer, P. (2020): When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. In: *Resources, Conservation and Recycling* 155. DOI: 10.1016/j.resconrec.2019.104666.

AKGGS (2023): Hygienesiches Spülen von Mehrweggeschirr aus Kunststoff im Außer-Haus-Betrieb für die sichere Wiederverwendung. Hg. v. Arbeitskreis Gewerbliches Geschirrspülen. Online verfügbar unter https://www.akggs.de/pressemitteilung/AK%20GGS_Merkblatt_Mehrweg_DE_01.2023.pdf#:~:text=,Auch, zuletzt geprüft am 10.06.2025.

APR (2025): The Plastic Recycling Process. Hg. v. Association of Plastics Recyclers. Online verfügbar unter <https://plasticsrecycling.org/how-recycling-works/>, zuletzt geprüft am 10.06.2025.

Arbeitskreis Gewerbliches Spülen (2025): Sammlung Normen, Gesetze und Regelwerke für Gewerbliches Spülen. Online verfügbar unter https://www.akggs.de/normen/PDFs/Normensammlung_%28V02_2025%29.pdf, zuletzt geprüft am 21.06.2025.

Auer, Maximilian; Eberle, Simon; Detering, Leon; Dubb, Lars; Schill, Raphael; Karatopi, Kiriaki (2025): präziSort - Ergebnisse der Verpackungsstudie. Online verfügbar unter https://www.hs-pforzheim.de/forschung/institute/institut_fuer_werkstoffe_und_werkstofftechnologien_prueflabor_fuer_materialuntersuchungen/verpackungsstudie, zuletzt geprüft am 24.07.2025.

AWARE: What is AWARE? Hg. v. WULCA. Online verfügbar unter <https://wulca-waterlca.org/aware/what-is-aware/>, zuletzt geprüft am 30.04.2025.

Begley, S. (2013): Science for hire - Trial over plastic exposes disclosure deficit, 18.07.2013. Online verfügbar unter Science for hire - Trial over plastic exposes disclosure deficit, zuletzt geprüft am 10.06.2025.

Behrens, Rudolf; Janßen, Ingrid; Kuhn, Ekart; Zimmermann, Peter (2018): Entwicklungen und Trends im Markt der Mehrweg Transport Verpackungen in Deutschland und Europa. Hg. v. EKUPAC.

Bertling, Jürgen; Blömer, Jan; Bersch, Lena (30.01.2025): Befragung und Datensammlung zu Spülpraxis von Mehrwegbechern im Zuge der Studie »Wash-Reuse« im Auftrag der Stiftung Initiative Mehrweg. geführt von Bertling, Jürgen; Bersch, Lena; Blömer, Jan. Interview mit Interviewpartner 1, Betreiber einer Becherwaschanlage.

Bertling, Jürgen; Dobers, Kerstin; Kabasci, Stephan; Schulte, Anna (2022): Kunststoffbasierte Mehrwegsysteme in der Circular Economy. Online verfügbar unter <https://publica.fraunhofer.de/entities/publication/7b363a1e-7283-4ed8-8fd1-3578e05ed0e6/details>, zuletzt geprüft am 04.11.2022.

Bezeraj, Erion; Debie, Simon; Arraez, Francisco J.; Reyes, Pablo; van Steenberge, Paul H. M.; D'hooge, Dagmar R.; Edeleva, Mariya (2025): State-of-the-art of industrial PET mechanical recycling: technologies, impact of contamination and guidelines for decision-making. In: *RSC Sustainability* 3 (5), S. 1996–2047.

Biedermann, Maurus; Grob, Koni (2010): Is recycled newspaper suitable for food contact materials? Technical grade mineral oils from printing inks. In: *Eur Food Res Technol* 230 (5), S. 785–796. DOI: 10.1007/s00217-010-1223-9.

Binderup, M. L.; Pedersen, G. A.; Vinggaard, A. M.; Rasmussen, E. S.; Rosenquist, H.; Cederberg, T. (2002): Toxicity testing and chemical analyses of recycled fibre-based paper for food contact. In: *Food additives and contaminants* 19 Suppl, S. 13–28. DOI: 10.1080/02652030110089878.

BKV (Hg.) (2024): Stoffstrombild Kunststoffe in Deutschland 2023 - Zahlen und Fakten zum Lebensweg von Kunststoffen. Kurzfassung. Conversio Market & Strategy GmbH. Online verfügbar unter <https://www.bkv-gmbh.de/files/bkv/studien/Kurzfassung%20Stoffstrombild%202023.pdf>.

BMEL (2017): Regulatorische Maßnahmen zu Mineralöl in Lebensmittelkontaktmaterialien und Lebensmitteln. Hg. v. U. Galle-Hofmann. Bundesministerium für Ernährung und Landwirtschaft. Online verfügbar unter <https://www.bfr.bund.de/cm/343/regulatorische-massnahmen-zu-mineraloel-in-lebensmittelkontaktmaterialien-und-lebensmitteln.pdf>.

BMUKN (2025): Wie viele Einweg-Becher werden jährlich verbraucht? Wie viele landen in der Umwelt? Hg. v. Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit. Online verfügbar unter <https://www.bundesumweltministerium.de/FA1060>, zuletzt geprüft am 10.09.2025.

Boz Noyan, E. C. (2024): Mechanical recycling of post-consumer polyethylene packaging waste. Thesis for the degree of doctor of philosophy. Online verfügbar unter https://research.chalmers.se/publication/542858/file/542858_Fulltext.pdf?utm_source=chatgpt.com, zuletzt geprüft am 10.06.2025.

Brown, Erina; MacDonald, Anna; Allen, Steve; Allen, Deonie (2023): The potential for a plastic recycling facility to release microplastic pollution and possible filtration remediation effectiveness. In: *Journal of Hazardous Materials Advances* 10, S. 100309. DOI: 10.1016/j.hazadv.2023.100309.

Bulach, W.; Dehoust, G.; Mayer, F.; Möck, A. (2022): Ökobilanz zu den Leistungen der dualen Systeme im Bereich des Verpackungsrecyclings. Öko-Institut e.V. Berlin, Darmstadt. Online verfügbar unter https://www.oeko.de/fileadmin/oekodoc/Duale_Systeme_Oekobilanz_Endbericht.pdf.

Bundesamt für Verbraucherschutz und Lebensmittelsicherheit (BVL) (2025): Rechtliche Rahmenbedingungen für Lebensmittelkontaktmaterialien. Hg. v. BVL. BVL. Online verfügbar unter https://www.bvl.bund.de/DE/Arbeitsbereiche/03_Verbraucherprodukte/03_AntragstellerUnternehmen/08_Rechtsvorschriften/02_LMKontaktmaterialien/bgs_LMKontaktmaterialien_rechtliche_grundlagen_node.html;jsessionid=637C66B35EA927E399D0A1CAE4DFAC20.internet962, zuletzt geprüft am 08.07.2025.

Bundesinstitut für Risikobewertung (2023): Empfehlung XXXVI Papiere, Kartons und Pappen für den Lebensmittelkontakt. BfR. Online verfügbar unter <https://www.bfr.bund.de/cm/343/XXXVI-Papiere--Kartons-und-Pappen-fuer-den-Lebensmittelkontakt.pdf>, zuletzt geprüft am 18.02.2025.

Castellani, F.; Aigner, J.; Berglykke Aagaard, S. (2022): Comparative Life Cycle Assessment (LCA). Packaging Solutions for the food segment. Ramboll. Online verfügbar unter https://www.fefco.org/sites/default/files/2022/FEFCO_Comparative_LCA_study.pdf.

Caye, N.; Marasus, Stefan; Nguyen, U.; Schüler, Kurt (2025): Bundesweite Erhebung von Daten zum Verbrauch von Getränken in Mehrweggetränkeverpackungen. Bezugsjahr 2022. Hg. v. Umweltbundesamt. Online verfügbar unter https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/03_2025_texte_mehrweggetraenkeverpackungen_kor.pdf, zuletzt geprüft am 10.06.2025.

Ceballos-Santos, Sandra; Sousa, David Baptista de; García, Pablo González; Laso, Jara; Margallo, María; Aldaco, Rubén (2024): Exploring the environmental impacts of plastic packaging: A comprehensive life cycle analysis for seafood distribution crates. In: *The Science of the total environment* 951, S. 175452. DOI: 10.1016/j.scitotenv.2024.175452.

Cendon Garcia, D. (2025): Vytal Global secures €14.2 million to scale tech-driven reusable packaging. Hg. v. EU startups.com. Online verfügbar unter <https://www.eu-startups.com/2025/03/vytal-global-secures-e14-2-million-to-scale-tech-driven-reusable-packaging/>, zuletzt aktualisiert am 11.03.2025, zuletzt geprüft am 10.06.2025.

CEPI (2016): Recovered Paper Quality Control Guidelines. CEPI. Online verfügbar unter <https://www.cepi.org/wp-content/uploads/2022/02/PaperforRecyclingQuality-Control-GuidelinesWITHANNEX.pdf>, zuletzt geprüft am 19.01.2025.

CEPI (2019): Food Contact Guidelines for the Compliance of Paper & Board Materials and Articles. Industry Guideline. European association representing the paper industry. Online verfügbar unter https://www.cepi.org/wp-content/uploads/2020/09/Food-Contact-Guidelines_2019.pdf, zuletzt geprüft am 17.01.2025.

CEPI (2025): KEY Statistics 2024. European pulp & paper industry. Hg. v. CEPI. Online verfügbar unter <https://www.cepi.org/wp-content/uploads/2025/07/Cepi-2024-Key-Statistics.pdf>, zuletzt geprüft am 01.10.2025.

Ceretti, Daniel V. A.; Edeleva, Mariya; Cardon, Ludwig; D'hooge, Dagmar R. (2023): Molecular Pathways for Polymer Degradation during Conventional Processing, Additive Manufacturing, and Mechanical Recycling. In: *Molecules (Basel, Switzerland)* 28 (5). DOI: 10.3390/molecules28052344.

Coperion (2025): Desodorierung im Kunststoff-Recycling: Schluss mit üblen Gerüchen. Hg. v. Coperion GmbH. Online verfügbar unter <https://coperion.com/de/industrien/kunststoff-recycling/kunststoff-recycling-geruchsentfernung#:~:text=Bereits%20bei%20der%20mechanischen%20Vorbehandlung,Weitere%20St%C3%B6rger%C3%BCche%20des>, zuletzt geprüft am 10.06.2025.

Cottafava, Dario; Costamagna, Mattia; Baricco, Marcello; Corazza, Laura; Miceli, Davide; Riccardo, Luigi E. (2021): Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups. In: *Sustainable Production and Consumption* 27, S. 228–241.

Cruz, S. A.; Zanin, M. (2003): Evaluation and identification of degradative processes in post-consumer recycled high-density polyethylene. In: *Polymer Degradation and Stability* 80 (1), S. 31–37. DOI: 10.1016/S0141-3910(02)00379-8.

CupPrint (2025): Double Wall Recyclable Paper Cups. Online verfügbar unter https://cupprint.com/product-category/recyclable-double-wall-paper-cups/?utm_source=chatgpt.com, zuletzt geprüft am 27.09.2025.

CVUA Stuttgart; Freistaat Sachsen; TU Dresden; Kantonales Labor Zürich (2012): Ausmaß der Migration unerwünschter Stoffe aus Verpackungsmaterialien aus Altpapier in Lebensmitteln. Ein Entscheidungshilfeprojekt des Bundesministeriums für Ernährung, Landwirtschaft und Verbraucherschutz. Hg. v. BELV. BELV.

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

Deutsche Umwelthilfe e.V. (Hg.) (2015): Becherheld – Mehrweg to go. DUH-Becherheldkampagne 2015. Online verfügbar unter <https://www.duh.de/becherheld/>, zuletzt geprüft am 16.12.2021.

Die Papierindustrie (2025): Leistungsbericht Papier. Online verfügbar unter https://www.papierindustrie.de/fileadmin/0002-PAPIERINDUSTRIE/07_Dateien/XX-LB/PAPIER_2025_Leistungsbericht_digital.pdf.

EG 1935/2004: Verordnung über Materialien und Gegenstände, die dazu bestimmt sind, mit Lebensmitteln in Berührung zu kommen. Online verfügbar unter <https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32004R1935&from=DE>, zuletzt geprüft am 22.02.2022.

Eisenträger, Frank (25.02.2025): Recyclingprozess für PS in Lebensmittelanwendungen und Herausforderungen der gesetzlichen Rahmenbestimmungen (EU 2022/1616). geführt von Bersch, Lena. Digital via MsTeams.

EMF (2015): Material Circularity Indicator. Hg. v. Ellen MacArthur. Online verfügbar unter <https://www.ellenmacarthurfoundation.org/material-circularity-indicator>, zuletzt aktualisiert am 03.05.2015, zuletzt geprüft am 23.07.2025.

EPRC (2024): Monitoring Report 2023 European. Declaration on Paper Recycling 2021-2030. Hg. v. European Paper Recycling Council (EPRC). Online verfügbar unter https://austropapier.at/wp-content/uploads/2024/08/23-00-EPRC-Recycling-Report.pdf?utm_source=chatgpt.com, zuletzt geprüft am 01.10.2025.

Euro Pool System (Hg.) (2021): Gemeinsam zur Kreislauf-Lieferkette. Online verfügbar unter <https://www.europoolsystem.com/de/>, zuletzt geprüft am 14.12.2021.

Europäische Kommission (2006): VERORDNUNG (EG) Nr. 2023/2006 DER KOMMISSION vom 22. Dezember 2006 über gute Herstellungspraxis für Materialien und Gegenstände, die dazu bestimmt sind, mit Lebensmitteln in Berührung zu kommen. (EG) Nr. 2023/2006. Fundstelle: EUR-Lex (L 384), S. 75–78. Online verfügbar unter <https://eur-lex.europa.eu/legal-content/DE/TXT/?uri=celex%3A32006R2023>.

Europäische Kommission (2011): Verordnung über Materialien und Gegenstände aus Kunststoff, die dazu bestimmt sind, mit Lebensmitteln in Berührung zu kommen. EU 10/2011, vom 2015. Fundstelle: Official Journal of the European Union. In: *Official Journal of the European Union*. Online verfügbar unter <https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:02011R0010-20150226&from=MT>, zuletzt geprüft am 30.03.2022.

Europäische Kommission (2022): Verordnung (EU) 2022/1616 der Kommission vom 15. September 2022 über Materialien und Gegenstände aus recyceltem Kunststoff, die dazu bestimmt sind, mit Lebensmitteln in Berührung zu kommen, und zur Aufhebung der Verordnung (EG) Nr. 282/2008 (Text von Bedeutung für den EWR). EK.

Europäische Kommission (2025a): Union register of novel technologies, recyclers, recycling processes, recycling schemes and decontamination installations. Informationsportal der Europäischen Kommission zu Lebensmittelkontaktmaterialien. Online verfügbar unter https://food.ec.europa.eu/food-safety/chemical-safety/food-contact-materials/plastic-recycling_en#union-register-of-novel-technologies-recyclers-recycling-processes-recycling-schemes-and-decontamination-installations, zuletzt aktualisiert am 11.07.2025, zuletzt geprüft am 11.07.2025.

Europäische Kommission (2025b): Verordnung (EU) 2025/351 zur Änderung der Verordnung (EU) Nr. 10/2011 über Materialien und Gegenstände aus Kunststoff, die dazu bestimmt sind, mit Lebensmitteln in Berührung zu kommen, zur Änderung der Verordnung (EU) 2022/1616 über Materialien und Gegenstände aus recyceltem Kunststoff, die dazu bestimmt sind, mit Lebensmitteln in

Berührung zu kommen, und zur Aufhebung der Verordnung (EG) Nr. 282/2008 sowie zur Änderung der Verordnung (EG) Nr. 2023/2006 über gute Herstellungspraxis für Materialien und Gegenstände, die dazu bestimmt sind, mit Lebensmitteln in Berührung zu kommen. Verordnung EU 2025/351, vom 21.02.2025. Online verfügbar unter https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=OJ:L_202500351, zuletzt geprüft am 08.07.2025.

Europäisches Parlament (2004): Verordnung (EG) Nr. 852/2004 über Lebensmittelhygiene, vom 04.03.2021. Fundstelle: EUR-Lex. Online verfügbar unter <https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:02004R0852-20210324>, zuletzt geprüft am 08.07.2025.

Europäisches Parlament (2025): Verordnung (EU) 2025/40 des Europäischen Parlaments und des Rates über Verpackungen und Verpackungsabfälle, zur Änderung der Verordnung (EU) 2019/1020 und der Richtlinie (EU) 2019/904 sowie zur Aufhebung der Richtlinie 94/62/EG. PPWR. Online verfügbar unter https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202500040, zuletzt aktualisiert am 14.02.2025, zuletzt geprüft am 14.02.2025.

Europäisches Parlament; Europäische Kommission (2004): REGULATION (EC) No 1935/2004 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC. Rahmenverordnung EU 1935/2004. Fundstelle: Official Journal of the European Union. In: *Official Journal of the European Union* (L 338/4).

European Directorate for the Quality of Medicines & HealthCare (EDQM) (2021): Paper and board used in food contact materials and articles. Technical Guideline.

FEFCO (Hg.) (2018): European Database for Corrugated Board Life Cycle Studies. Corrugated Packaging; Cepi ContainerBoard. Online verfügbar unter <https://www.fefco.org/download/file/fid/2626>, zuletzt geprüft am 10.12.2021.

FEFCO (2022): Recycling vs. Reuse for Packaging. Bringing the Science into the Packaging Debate. Online verfügbar unter https://www.fefco.org/sites/default/files/2022/FEFCO_Visual_Overview_v8.1.pdf, zuletzt geprüft am 02.09.2022.

FEFCO (2024): European Database for Corrugated Board Life Cycle Studies. Hg. v. FEFCO. Online verfügbar unter https://www.fefco.org/lca/data?utm_source=chatgpt.com, zuletzt geprüft am 01.10.2025.

Finish (2025): Kann ich Kunststoff in der Spülmaschine reinigen? Hg. v. RB Hygiene Home AG. Online verfügbar unter <https://www.finish.ch/geschirrspuel-leitfaden/einraumen/kunststoff/>, zuletzt geprüft am 10.06.2025.

Fischer, Thomas (02.05.2025): So verringert sich der Abfall nicht. Interview. 320° Deutschlands Online-Magazin für die Circular Economy.

Foteinis, Spyros (2020): How small daily choices play a huge role in climate change: The disposable paper cup environmental bane. In: *Journal of Cleaner Production* 255, S. 120294.

Gallego-Schmid, Alejandro; Mendoza, Joan Manuel F.; Azapagic, Adisa (2018): Improving the environmental sustainability of reusable food containers in Europe. In: *The Science of the total environment* 628-629, S. 979–989. DOI: 10.1016/j.scitotenv.2018.02.128.

Gandhi, Neeti; Farfaras, Nicholas; Linda Wang, Nien-Hwa; Chen, Wan-Ting (2021): Life Cycle Assessment of Recycling High-Density Polyethylene Plastic Waste. In: *Journal of Renewable Materials* 9 (8), S. 1463–1483.

Gesellschaft für Verpackungsmarktforschung mbH (GVM) (2018): Abfallaufkommen durch Einweggeschirr und andere Verpackungen für den Sofortverzehr. Online verfügbar unter https://www.nabu.de/imperia/md/content/nabude/abfallpolitik/181022_gvm-studie_einweggeschirr_sofortverzehr.pdf, zuletzt geprüft am 23.03.2022.

DIN EN 17735, 2023: Gewerbliche Spülmaschinen – Hygieneanforderungen und Prüfung.

GKV (2022): Neue Regeln für Kunststoff-Rezyklate im Kontakt mit Lebensmitteln. Leitlinien.

Glausitz, Josie (2014): Kunststoff mit Nebenwirkungen. Online verfügbar unter [gefaehrlich-sind-bisphenol-a-und-seine-ersatzstoffe/1285126](#), zuletzt geprüft am 11.06.2025.

Gneuß (2025): Entgasung und Dekontamination. Hg. v. Gmneuß Kunststofftechnik GmbH. Online verfügbar unter <https://www.gneuss.com/de/turnkey/entgasung-und-dekontamination/#:~:text=Entgasung%20und%20Dekontamination%20von%20Polymeren,Ein%20Hersteller%20von%20Verpackungsfolien>, zuletzt geprüft am 10.06.2025.

Gnoffo, Chiara; Arrigo, Rossella; Frache, Alberto (2025): Mechanical recycling of HDPE-based packaging: Interplay between cross contamination, aging and reprocessing. In: *Polymer Degradation and Stability* 236, S. 111290. DOI: 10.1016/j.polymdegradstab.2025.111290.

Grummt, S. (2022): Praxis der Sortierung und Verwertung von Verpackungen im Sinne des §21 VerpackG 2021/2022. TEXTE 125/2022. Teilbericht 1. Umweltbundesamt. Online verfügbar unter https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2023-01-05_texte_125-2022_praxis_der_sortierung_und_verwertung_von_verpackungen.pdf, zuletzt geprüft am 18.07.2025.

Grummt, S.; Fabian, M. (2023): Praxis der Sortierung und Verwertung von Verpackungen im Sinne des § 21 VerpackG 2021/2022. Teilbericht 2. Hg. v. UBA. Dessau-Roßlau (TEXTE, 120), zuletzt geprüft am 15.07.2025.

Hartard, Susanne; Theobald, Klara (17.01.2025): Austausch zu Forschungsaktivitäten zu Mehrwegverpackungen am Umweltcampus Birkenfeld der Hochschule Trier. geführt von Bersch, Lena; Bertling, Jürgen. Online.

Hesseler, Ludger (07.01.2025): Befragung und Datensammlung zu Prozessdaten von MEIKO Band- und Haubenspülmaschinen im Zuge der Studie »Wash-Reuse« im Auftrag der Stiftung Initiative Mehrweg. geführt von Bertling, Jürgen; Bersch, Lena. Virtuell, via Teams.

Hirsilä, Paula (2023): Recycled plastic, paper, and board in food contact materials - overview of regulations. Measurelabs. Online verfügbar unter <https://measurlabs.com/blog/recycled-food-contact-materials/>, zuletzt geprüft am 16.07.2025.

Höke, Ulrich (2013): Forderungen der Papierfabriken an die Qualität des Altpapiers für die Herstellung grafischer Papiere. Qualität des gesammelten Altpapiers und Aufbereitungsverfahren. In: Thomé-Kozmiensky, K. und d. Goldmann (Hg.): Recycling und Rohstoffe (Recycling und Rohstoffe, 6).

Huhtamaki (2025): Microwavable cups and food containers. Online verfügbar unter https://www.huhtamaki.com/en-us/north-america/consumer-goods/microwave-hot-cup/?utm_source=chatgpt.com, zuletzt geprüft am 03.10.2025.

IFCO (2025): IFCO Smartcycle - Service Center Operations. Online verfügbar unter <https://www.youtube.com/watch?v=QlQivOD3vJQ>, zuletzt geprüft am 09.07.2025.

IHO (2024): Reinigung und Desinfektion in der professionellen (Groß-)Küche. Hg. v. Industrieverband Hygiene und Oberflächenschutz, zuletzt geprüft am <https://www.iho.de/wp-content/uploads/09.01.2024-IHO-Broschuere-Grosskuechenhygiene-A5-07-1.pdf#:~:text=Gem%C3%A4%C3%9F%20dem%20Sinnerschen%20Kreis%20stellen,ist%20dieses%20jeweils%20nur%20in.>

Jeswani, Harish; Krüger, Christian; Russ, Manfred; Horlacher, Maike; Antony, Florian; Hann, Simon; Azapagic, Adisa (2021): Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. In: *The Science of the total environment* 769, S. 144483.

Jin, Huiying; Gonzalez-Gutierrez, Joamin; Oblak, Pavel; Zupančič, Barbara; Emri, Igor (2012): The effect of extensive mechanical recycling on the properties of low density polyethylene. In: *Polymer Degradation and Stability* 97 (11), S. 2262–2272. DOI: 10.1016/j.polymdegradstab.2012.07.039.

Joana Almeida; Marie Le Pellec; Jonas Bengtsson (2018): Reusable coffee cups life cycle assessment and benchmark.

Johansson, Anders; Hallmans, Göran; Holm, Stig E.; Olofsson, Carin; Gref, Rolf; Svensson, Kjetil et al. (2001): Microflora in paperboard with various contents of recycled fibers. In: *Nordic Pulp & Paper Research Journal* 16 (1), S. 40–45. DOI: 10.3183/npprj-2001-16-01-p040-045.

Kaitinnis, Nina (2019): Ökobilanzieller Vergleich von zwei Abfallsortieranlagen für Leichtverpackungen nach altem und neuem Stand der Technik. Bachelorarbeit. TH Bingen, Bingen.

Kasper, Johann B.; Parker, Luke A.; Postema, Sander; Höppener, Elena M.; Leighton, Alexandra H.; Finnegan, Alexander M. D. et al. (2025): Losses and emissions in polypropylene recycling from household packaging waste. In: *Waste management (New York, N.Y.)* 191, S. 230–241.

Kauertz, b.; Schlecht, S.; Markwardt, S.; Rubik, F.; Heinrich, J.; Kolbe, P.; Hake, Y. (2019): Untersuchung der ökologischen Bedeutung von Einweggetränkebechern im Außer-Haus-Verzehr und mögliche Maßnahmen zur Verringerung des Verbrauchs. Hg. v. Umweltbundesamt (TEXTE, 29/2019). Online verfügbar unter https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-02-20_texte_29-2019_einweggetraenkebechern_im_ausser-haus-verzehr_final.pdf.

Kent, R. (2011): Energy Management in Plastic Processing. A Signposting Guide by The British Plastic Federation. Hg. v. BFP.

Knappe, F.; Reinhardt, J.; Kauertz, b.; Oetjen-Dehne, R.; Buschow, N.; Ritthoff, M. et al. (2021): Technische Potenzialanalyse zur Steigerung des Kunststoffrecyclings und des Rezyklateinsatzes. Hg. v. Umweltbundesamt (TEXTE, 92/2021).

Knoben, Niek; Vanhouttem, Max; Wypkema, Aike; Subramanian, Nithya (2025): Monitoring Antioxidant Consumption and Build-Up in Polypropylene During Open-Loop and Closed-Loop Mechanical Recycling. In: *Materials (Basel, Switzerland)* 18 (7). DOI: 10.3390/ma18071640.

Kölmel, Romy (19.12.2024): Herausforderungen für Papierverarbeitung durch beschichtete Papierverpackungen (Wachs, PE) und Lebensmittelverunreinigungen. geführt von Bersch, Lena. Telefonisch.

Krämer, Johannes; La Guedes de Cruz, Gema Carmen; Kern, Wolfgang; Roitner, Julia; Witschnigg, Andreas; Rittmannsberger, Franz; Schnetzinger, Karl (2024): Increasing the melt viscosity of post-consumer recycled polypropylene via E-Beam techniques. In: *Radiation Physics and Chemistry* 222, S. 111846. DOI: 10.1016/j.radphyschem.2024.111846.

Kunststoffindustrie Online (2023): Schmelzefilter verbessert Kosteneffizienz bei Kunststoffrecycling. Hg. v. Kunststoffindustrie Online. Online verfügbar unter <https://www.kunststoffindustrie-online.de/produktion/schmelzefilter-verbessert-kosteneffizienz-bei-kunststoffrecycling#:~:text=sich%20zum%20Filterieren%20der%20g%C3%A4ngigen,Speziell%20im%20Folienrecycling%20er%C3%B6ffnet,zuletzt%20gepr%C3%BCft%20am%2010.06.2025>.

Langberg, Håkon A.; Arp, Hans Peter H.; Castro, Gabriela; Asimakopoulos, Alexandros G.; Knutsen, Heidi (2024): Recycling of paper, cardboard and its PFAS in Norway. In: *Journal of Hazardous Materials Letters* 5, S. 100096. DOI: 10.1016/j.hazl.2023.100096.

Larrain, Macarena; van Passel, Steven; Thomassen, Gwenny; van Gorp, Bart; Nhu, Trang T.; Huysveld, Sophie et al. (2021): Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. In: *Resources, Conservation and Recycling* 170, S. 105607.

DIN 10522, 2006: Lebensmittelhygiene - Gewerbliches maschinelles Spülen von Mehrwegkästen und Mehrwegbehältnissen für unverpackte Lebensmittel - Hygieneanforderungen, Prüfung.

DIN 10516, 2020: Lebensmittelhygiene - Reinigung und Desinfektion.

Lebensmittelverband Deutschland (Hg.) (2020): Merkblatt "Pool-Geschirr". Hygiene beim Umgang mit Mehrweggeschirren innerhalb von Pfand-Poolsystemen. Online verfügbar unter <https://www.lebensmittelverband.de/de/lebensmittel/sicherheit/hygiene/hygiene-beim-umgang-mit-mehrweg-bechern-behaeltnissen-pool-geschirr>, zuletzt geprüft am 17.03.2022.

Lebensmittelverband Deutschland e.V. (2019): MERKBLATT „Coffee to go“-Becher. Hygiene beim Umgang mit kundeneigenen Bechern zur Abgabe von Heißgetränken in Bedienung oder Selbstbedienung.

Lebensmittelverband Deutschland e.V. (2020): Merkblatt „Mehrweg-Behältnisse“. Hygiene beim Umgang mit kundeneigenen Behältnissen zur Abgabe von Lebensmitteln in Bedienung oder Selbstbedienung. Berlin.

Levi, Marinella; Cortesi, Sara; Vezzoli, Carlo; Salvia, Giuseppe (2011): A Comparative Life Cycle Assessment of Disposable and Reusable Packaging for the Distribution of Italian Fruit and Vegetables. In: *Packag. Technol. Sci.* 24 (7), S. 387–400. DOI: 10.1002/pts.946.

Lewis, Yvonne; Gower, Alexandra; Notten, Philippa (2021): Single-use beverage cups and their alternatives. Recommendations from Life Cycle Assessments. Online verfügbar unter <https://www.lifecycleinitiative.org/library/single-use-beverage-cups-and-their-alternatives-lca/>, zuletzt geprüft am 04.08.2021.

Ligthart, T. N. (2007): Single use Cups or Reusable (coffee) Drinking Systems: An Environmental Comparison. TNO. Netherlands. Online verfügbar unter <https://www.tno.nl/media/2915/summary-research-drinking-systems.pdf>.

LUBW (2020): 03 03 03 Zellstoffherstellung, Papierherstellung. Abfallsteckbrief im Rahmen des Informationsportals Abfallbewertung IP@. Hg. v. Informationsportal Abfallbewertung. Online verfügbar unter https://www.abfallbewertung.org/repge.php?char_id=0303_Altpa&report=ipa&kapitel=1&lang_id=de&avv=&synon=>active=no, zuletzt geprüft am 22.09.2025.

Martin, S.; Bunsen, A.; Citroth, A. (2018): Case Study Ceramic Cup vs. Paper Cup. Greendelta GmbH. Online verfügbar unter <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahU-KEwi8x8m889v2AhWPlqQKHbOkAbIQFnoECAYQAQ&url=https%3A%2F%2Fnexus.openlca.org%2Fws%2Ffiles%2F6229&usq=AOvVaw0NCfTz81occ9BIJY-qtujm>.

Meyer, J.; Schubert, A.; Trautmann, A.; Kirschbaum, S.; Kausch, C.; Probst, T. (2009): Leitfaden Energieeffizienz für die Recyclingindustrie. Hg. v. Arbeitsgemeinschaft Branchenenergiekonzept Recycling.

MIMASA (2025): Kistenwaschanlagen - Produktportfolio. Online verfügbar unter <https://mimasa.com/de/start.html>, zuletzt geprüft am 09.07.2025.

MM Group (2025): Recycled cartonboard with barrier for safe food packaging. Hg. v. Mayr-Melnhof Karton Aktiengesellschaft. Online verfügbar unter https://mm.group/board-paper/innovation/foodboard/?utm_source=chatgpt.com, zuletzt geprüft am 03.10.2025.

Nielsen, T.; Damant, A. P.; Castle, L. (1997): Validation studies of a quick test for predicting the sorption and washing properties of refillable plastic bottles. In: *Food additives and contaminants* 14 (6-7), S. 685–693. DOI: 10.1080/02652039709374580.

Pachaly, Patrick (2021): Coffee-to-Go Becher (ReCup). Interview mit Kerstin Dobers und Jürgen Bertling. Digital via Microsoft Teams.

DIN EN 643, 01.11.2014: Papier, Karton und Pappe – Europäische Liste der Altpapier-Standardsorten; Deutsche Fassung EN 643:2014, zuletzt geprüft am 18.02.2025.

Papstar (2025a): Pappbecher "pure" unbeschichtet. Hg. v. Papstar GmbH. Online verfügbar unter <https://www.papstar.com/solutions/pappbecher-recycling>, zuletzt geprüft am 27.09.2025.

Papstar (2025b): Pappbecher-Recycling. Hg. v. Papstar GmbH. Online verfügbar unter <https://www.papstar.com/solutions/pappbecher-recycling>, zuletzt geprüft am 27.09.2025.

Pin, Jean-Mathieu; Soltani, Iman; Negrier, Keny; Lee, Patrick C. (2023): Recyclability of Post-Consumer Polystyrene at Pilot Scale: Comparison of Mechanical and Solvent-Based Recycling Approaches. In: *Polymers* 15 (24). DOI: 10.3390/polym15244714.

Pivnenko, Kostyantyn; Laner, David; Astrup, Thomas F. (2016): Material Cycles and Chemicals: Dynamic Material Flow Analysis of Contaminants in Paper Recycling. In: *Environmental Science & Technology* 50 (22), S. 12302–12311. DOI: 10.1021/acs.est.6b01791.

Pladerer, Christian; Meissner, Markus; Dinkel, Fredy; Zschokke, Mischa; Dehoust, Günter; Schüler, Doris (2008a): Comparative Life Cycle Assessment of various Cup Systems for the Selling of Drinks at Events. Focussing on major events such as the European Football Championships UEFA EURO 2008(TM) in Austria and Switzerland as well as the German "Bundesliga". Österreichisches Ökologie-Institut; Carbotech AG; Öko-Institut e.V. Deutschland. Online verfügbar unter http://www.meucopoeco.com.br/environmental_study.pdf.

Pladerer, Christian; Meissner, Markus; Dinkel, Fredy; Zschokke, Mischa; Dehoust, Günter; Schüler, Doris (2008b): Comparative Life Cycle Assessment of various Cup Systems for the Selling of Drinks at Events. Focussing on major events such as the European Football Championships UEFA EURO 2008(TM) in Austria and Switzerland as well as the German "Bundesliga". Österreichisches Ökologie-Institut; Carbotech AG; Öko-Institut e.V. Deutschland. Online verfügbar unter http://www.meucopoeco.com.br/environmental_study.pdf.

Plastic Recyclers Europe (2024): Recyclability Evaluation Protocol. Hg. v. Plastic Recyclers Europe.

Potting, José; van der Harst, Eugenie (2015): Facility arrangements and the environmental performance of disposable and reusable cups. In: *Int J Life Cycle Assess* 20 (8), S. 1143–1154. DOI: 10.1007/s11367-015-0914-7.

Rasines, Laura; San Miguel, Guillermo; Corona, Blanca; Aguayo, Encarna (2024): Addressing the circularity and sustainability of different single-use and reusable crates used for fresh fruit and

vegetables packaging. In: *Food Packaging and Shelf Life* 46, S. 101391. DOI: 10.1016/j.fpsl.2024.101391.

Ravishankar, Kartik; Ramesh, Praneeth Srivanth; Sadhasivam, Balaji; Raghavachari, Dhamodharan (2018): Wear-induced mechanical degradation of plastics by low-energy wet-grinding. In: *Polymer Degradation and Stability* 158, S. 212–219. DOI: 10.1016/j.polymdegradstab.2018.10.026.

ReCup (2025): RECUP – die Mehrwegbecher für die Gastronomie. Online verfügbar unter https://recup.de/mehrwegbecher/?utm_term=mehrweg%20becher&utm_campaign=S-DE-RECUP-Specific&utm_source=adwords&utm_medium=ppc&hsa_acc=5205217405&hsa_cam=18562184598&hsa_grp=140122120217&hsa_ad=627400322070&hsa_src=g&hsa_tgt=kwd-313868878290&hsa_kw=mehrweg%20becher&hsa_mt=p&hsa_net=adwords&hsa_ver=3&gad_source=1&gad_campaignid=18562184598&gclid=Cj0KCQjwrojHBhDdARIsAJdEJ_fZYGiUA5qBm66wXVXlxQD_7oSokAGliDn2SFVGQu_hUJYFe7o91BYaAkkZEALw_wcB, zuletzt geprüft am 05.10.2025.

Recycling Today (2025): What Is a Plastic Washing System? How It Works. Online verfügbar unter <https://www.recyclingtoday.org/blogs/news/what-is-a-plastic-washing-system-how-it-works#:~:text=2>, zuletzt geprüft am 10.06.2025.

Roosen, Martijn; Harinck, Lies; Ügdüler, Sibel; Somer, Tobias de; Hucks, Amaury-Gauvain; Belé, Tiago G. A. et al. (2022): Deodorization of post-consumer plastic waste fractions: A comparison of different washing media. In: *The Science of the total environment* 812, S. 152467.

Schaich, Dirk (29.01.2025): Befragung und Datensammlung zu Spülpraxis von Mehrwegbechern im Zuge der Studie »Wash-Reuse« im Auftrag der Stiftung Initiative Mehrweg. geführt von Bertling, Jürgen; Blömer, Jan. Voerde.

Schill, Raphael (2025): Detailergebnisse der Verpackungsstudie präziSort im Bereich To-Go-Getränkebecher, 23.07.2025. E-Mail an Lena Bersch.

Schmid, Petra; Welle, Frank (2020): Chemical Migration from Beverage Packaging Materials—A Review. In: *Beverages* 6 (2), S. 37.

Schyns, Zoé O. G.; Shaver, Michael P. (2021): Mechanical Recycling of Packaging Plastics: A Review. In: *Macromolecular rapid communications* 42 (3), e2000415. DOI: 10.1002/marc.202000415.

Shen, Xiaoning; Hed, Yvonne; Annfinsen, Steffen; Singh, Naveen; Anwar, Hany; Mylvaganam, Bavan et al. (2025): Investigating Polyethylene Terephthalate Beverage Packaging: Impact of Recycled Content on Acetaldehyde, Benzene, and Other Contaminants. In: *J Polym Environ* 33 (5), S. 2362–2370. DOI: 10.1007/s10924-025-03544-1.

Sobhani, Zahra; Palanisami, Thava (2025): Emerging contaminants in organic recycling: Role of paper and pulp packaging. In: *Resources, Conservation and Recycling* 215, S. 108070.

Sphera (2025): LCA for Experts / MLC Database: Sphera. Online verfügbar unter www.sphera.com.

Stora Enso (2025): Cupforma Natura PE. Online verfügbar unter https://www.storaenso.com/-/media/documents/download-center/documents/product-specifications/paperboard-materials/cupforma-natura-pe-15-us.pdf?utm_source=chatgpt.com, zuletzt geprüft am 03.10.2025.

Straková, Jitka; Schneider, Julie; Cingotti, Natacha (2021): Throwaway Packaging, Forever Chemicals. European wide survey of PFAS in disposable food packaging and tableware. CHEM Trust; BUND; HEAL; Tegengif; Générations Futures; Arnika Association; IPEN; Danish Consumer Council.

Online verfügbar unter https://chemtrust.org/wp-content/uploads/PFASreport_FCM_May2021.pdf, zuletzt geprüft am 11.07.2025.

Swinnerton, S.; Su, J.; Tsai, Candace S. J. (2024): The emission and physicochemical properties of airborne microplastics and nanoplastics generated during the mechanical recycling of plastic via shredding. In: *Scientific reports* 14 (1), S. 24755. DOI: 10.1038/s41598-024-73775-0.

UBA (2025): Recyclingpapier ist gut für die Umwelt. Hg. v. Umweltbundesamt. Online verfügbar unter <https://www.umweltbundesamt.de/umwelttipps-fuer-den-alltag/haushalt-wohnen/papier-recyclingpapier#undefined>, zuletzt aktualisiert am 20.08.2025, zuletzt geprüft am 22.08.2025.

Uekert, Taylor; Singh, Avantika; DesVeaux, Jason S.; Ghosh, Tapajyoti; Bhatt, Arpit; Yadav, Geetanjali et al. (2023): Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. In: *ACS Sustainable Chem. Eng.* 11 (3), S. 965–978.

Umweltbundesamt (2025): Einsatz von PFAS in der Papierindustrie. UBA. Online verfügbar unter <https://www.umweltbundesamt.de/einsatz-von-pfas-in-der-papierindustrie>, zuletzt aktualisiert am 10.07.2025, zuletzt geprüft am 10.07.2025.

Umweltbundesamt (Hg.) (2024): Altpapier. Hg. v. Umweltbundesamt. Online verfügbar unter <https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/altpapier#vom-papier-zum-altpapier>, zuletzt geprüft am 23.07.2025.

Utopia (2023): Coffee-to-go: Wo du den Becher jetzt am Automaten zurückgeben kannst, zuletzt geprüft am 17.09.2025.

VerpackG (2021): Gesetz über das Inverkehrbringen, die Rücknahme und die hochwertige Verwertung von Verpackungen. VerpackG, vom zuletzt geändert durch Artikel 2 G. v. 22.09.2021 BGBl. I S. 4363. Online verfügbar unter <https://www.gesetze-im-internet.de/verpackg/VerpackG.pdf>, zuletzt geprüft am 31.01.2022.

Wacker, Stephan (2024a): Ab Januar bei Lidl: Joghurtbecher aus mechanisch recyceltem Polystyrol. Online verfügbar unter <https://320grad.de/2024/12/22/ab-januar-bei-lidl-joghurtbecher-aus-mechanisch-recyceltem-polystyrol/>, zuletzt aktualisiert am 13.01.2025, zuletzt geprüft am 15.01.2025.

Wacker, Stephan (2024b): EU-Verpackungs-verordnung: Stimmen zur Einigung. Hg. v. 320° - Deutschlands Online-Magazin für die Circular Economy. 320° - Deutschlands Online-Magazin für die Circular Economy. Online verfügbar unter <https://320grad.de/2024/03/05/eu-verpackungs-verordnung-stimmen-zur-einigung/>, zuletzt aktualisiert am 26.04.2024, zuletzt geprüft am 11.07.2025.

WestRock (2025): Fold-Pak®: Verpackungslösungen für unterwegs und zum Mitnehmen. Nachhaltigkeit und Leistung für unterwegs. Online verfügbar unter https://de.westrock.com/products/folding-cartons/fold-pak-to-go-packaging?utm_source=chatgpt.com, zuletzt geprüft am 03.10.2025.

Yadav, Pooja; Silvenius, Frans; Katajajuuri, Juha-Matti; Leinonen, Ilkka (2024): Life cycle assessment of reusable plastic food packaging. In: *Journal of Cleaner Production* 448, S. 141529. DOI: 10.1016/j.jclepro.2024.141529.

Zimmermann, Lisa; Dierkes, Georg; Ternes, Thomas A.; Völker, Carolin; Wagner, Martin (2019): Benchmarking the in Vitro Toxicity and Chemical Composition of Plastic Consumer Products. In: *Environmental Science & Technology* 53 (19), S. 11467–11477.