

Final report BWPLUS

RohWerKBaWü: Raw material and material recycling of waste
fractions previously only
thermally recycled in Baden-Württemberg

from

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und Energiewirtschaft**

Summary

In this project, waste streams generated in Baden-Württemberg, which have previously only been thermally treated, were qualified for raw material and material recovery. The innovative sorting technologies from Polysecure and the new recycling process from CARBOWEST (Carboliq process) were applied and demonstrated.

The aim of the project was to pre-process existing alternative fuels to obtain a new quality of alternative fuel that could then be subjected to mechanical and/or feedstock recycling. The project tested a marker-based sorting approach for specific sorting of previously inseparable composite materials. This would also enable material and/or feedstock recycling. The resulting EBS++ quality was successfully operated at the CARBOWEST pilot plant, resulting in a marketable, drop-in compatible product.

A petroleum substitute product was produced. As **the project concluded**, a technology and business analysis was conducted for the implementation of corresponding resilient closed-loop recycling processes. These findings not only provided a concrete basis for a commercial application at KORN, but also formed the basis for developing a showcase for marketing to other recycling companies in Baden-Württemberg with similar input material qualities. The project aims to generate acceptance among relevant target groups to further advance the circular transformation and independence from fossil raw materials in Baden-Württemberg.

We thank the state of Baden-Württemberg for providing the funding. We also thank the Karlsruhe Project Management Agency (PTKA), especially Mr. Decker, for his excellent support and guidance, as well as the Ministry of the Environment for its review and support.

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List of abbreviations

List of abbreviations

EBS

CLR

NIR

NE

OS

FTIR

S4C

Alternative fuel

Circular Liquid Resource

Near-infrared spectroscopy

Non-ferrous

Original substance

Fourier-transformed infrared

Sort4Circle

1 Introduction

1.1 motivation

Plastics are indispensable in our world as versatile, high-performance, and, in many applications, CO₂-efficient materials. Unfortunately, most plastic applications are not yet recyclable. The European Union aims to change this. With the European Green Deal and numerous new regulations, the circular economy is to be promoted for plastics as well. The goal: Starting from 4.6 million tons, 10 million tons of recycled materials are to be used instead of virgin plastics by 2025. Along with this, the EU's material recycling rate for plastic packaging is to be increased from the current level of around 20% to 55% (EU).

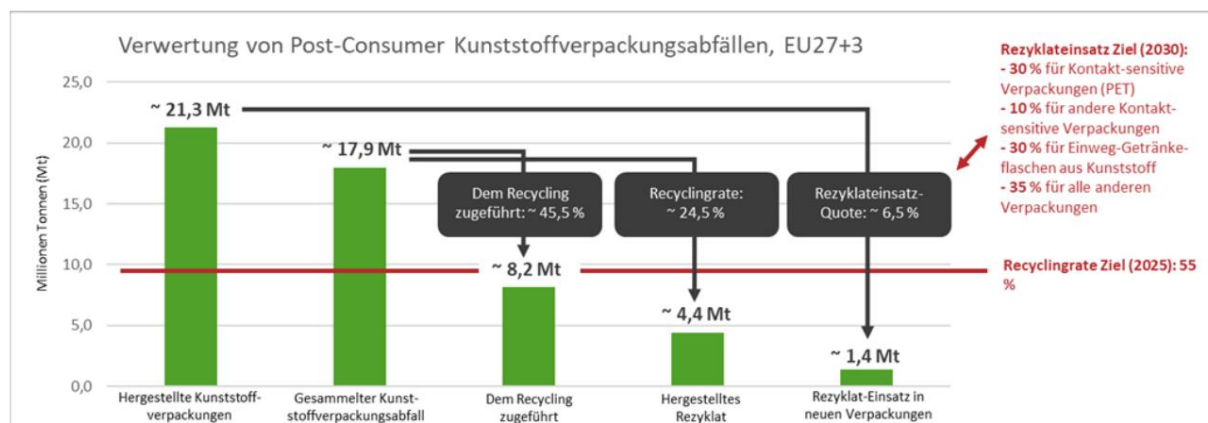


Figure 1 Recovery of post-consumer plastic packaging waste in the EU27+3 2020, target rates according to the EU Regulation on packaging and packaging waste

Looking at these figures for Germany, of the approximately 6.57 million tons of plastic waste collected in 2021, more than half was used for energy recovery and only about 2.64 million tons for material recycling. This resulted in only 1.65 million tons of recyclate being used in new plastic products.

With regard to plastic packaging, even the most modern German LVP (lightweight packaging) sorting facilities only achieve a recycling rate of around 30% when considering the actual amount recycled in relation to the actual input of packaging plastic into the sorting facilities. Increasing this to a true 55% (EU) or even to the 63% stipulated by the German Packaging Act therefore requires significantly improved sorting technology.

In accordance with current technological standards, sensor-based optical methods are most commonly used for sorting plastic waste. Near-infrared (NIR) spectrometry is particularly prevalent in this context. For this purpose, a specific plastic fraction was identified in each of several NIR sorters connected in series and pneumatically separated from the remaining waste stream.

The objects to be sorted are illuminated with halogen lamps, and the absorption bands characteristic of the respective polymer are recorded in the reflection spectrum. In practice, however, the spectra can be masked by additives or formulation variations, which impairs the reliability of the detection. Consequently, NIR technology is practically limited to the identification of the main polymers (e.g., PE, PET, PS, PP), meaning that important subclasses or application-relevant specifications cannot be distinguished. For example, polymers with different additives are not differentiated, application-specific differentiation (e.g., food vs. non-food) is not represented, or composite materials are incorrectly assigned to only one polymer type.

The latter case was specifically considered in the present project. Ultimately, a significant proportion of the plastics remain in the lower-grade mixed fraction or in the sorting residue, and corresponding contamination of the recyclable material also occurs.

Plastic fractions. Consequently, subsequent sorting at the recycler can result in a further mass loss of up to 35% of the fractions to be processed.

There is therefore a clear need to improve the accuracy and efficiency of automatic sorting through an innovative sorting system that enables the differentiation of pure, specific fractions according to market needs and the requirements of a CO₂-efficient circular economy – the TBS-light and SORT4CIRCLE® processes from Polysecure can offer a crucial solution for this.

1.2 Objective

The aim of the project was to process the refuse-derived fuel (RDF) from KORN Recycling GmbH in such a way as to successfully obtain a new quality of refuse-derived fuel that could be subjected to mechanical and/or feedstock recycling. This was achieved.

in a balance run in the area developed by carboliq/RECENSO and by CARBOWEST

The pilot plant for the liquefaction of various waste fractions was tested. The objective of the data collection run—to obtain basic data, such as an integrated mass, energy, and material balance, and to use this data as a basis for initial investment planning for a commercial application of this novel recycling technology at KORN—was achieved.

At the same time, a marker-based sorting approach was tested, which enables the specific sorting of previously inseparable composite materials, which can then also be recycled materially and/or as raw materials.

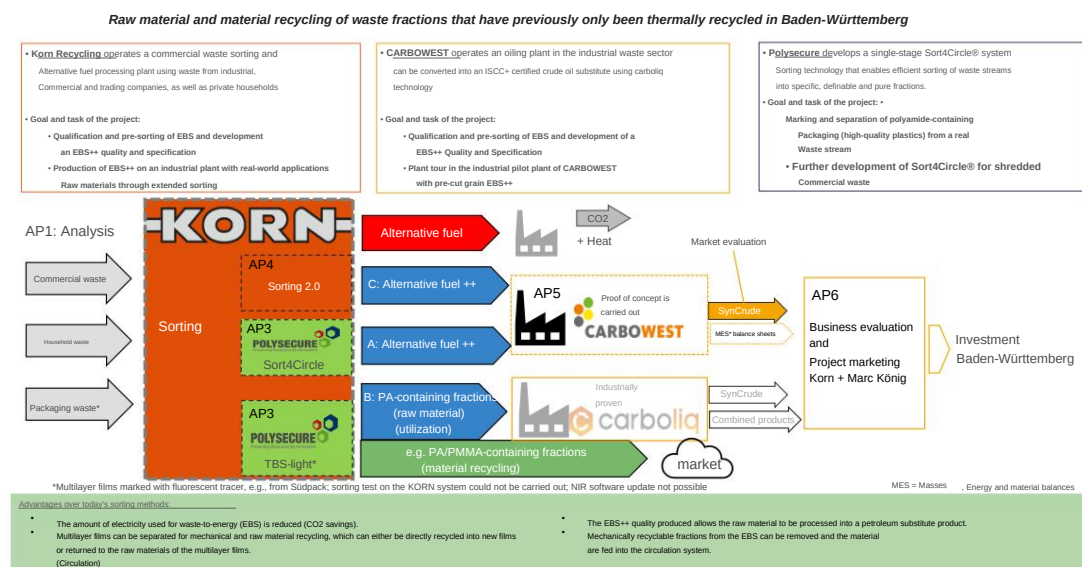


Figure 2 Summary of projects within the RohWerKBaWü project

1.3 Proceed

On the one hand, the feasibility of a **closed loop for a plastic packaging fraction** (LDPE/PA film packaging) should be demonstrated as an example.

Implementation requires a new sorting technology (TBS-light from Polysecure), a new chemical recycling process (carboliq process used at **CARBOWEST**) and implementation by recycling companies (e.g. KORN Recycling).

The combined, profitable added value amounts to approximately 1,000 euros per ton of material.

In Germany alone, the LDPE/PA fraction amounts to approximately 100,000 tons per year, and in Europe to approximately 600,000 tons per year. This translates into a value creation potential of **around €600 million**.

Furthermore, there are other fractions of packaging waste that could be recycled at a similarly high level and within a closed-loop system. This opens up further recycling potential. These additional fractions also represent further scientific opportunities.

Potential uses are limited because the processing methods, especially chemical and physical processes, must be developed and validated each time.

On the other hand, the project explored how EBS++ could be produced and commercially utilized. Subsequent market activity ensured that the product also met the quality requirements of the customers. CARBOWEST owns

We have many years of experience in the operation and distribution of pyrolysis oils based on various waste-derived secondary raw materials. The results show that 3 to 6 million tons of previously unusable waste can be processed into raw materials, thus saving CO2 emissions. (Weppel, Ufermann, & Aschauer, 2023)

Based on the mass, energy, material, and revenue/cost data, an initial investment estimate can be prepared for a potential plant at KORN's Albstadt site. The generated figures can also be used to prepare permit applications, as they are based on real data. Furthermore, the length of the operational trial allows for the issuance of necessary process guarantees, significantly reducing the investment risk in Baden-Württemberg. For CARBOWEST, this also offers the opportunity to expand the range of processable material classes to include additional RDF grades.

Regarding knowledge transfer, the project resulted in two scientific publications and at least one practice-oriented publication, jointly developed by the project consortium. The latter is a type of white paper on the application of the methods, including their economic context. The project results were tailored to specific target groups, including users of the technology, experts in the relevant disciplines, policymakers and legislators, and the general public. In addition, several events and project meetings were held to present and discuss the results. These events were specifically designed for the target markets, with at least one event taking the form of an on-site transfer workshop at Korn or Polysecure.

Polysecure reported on the project via its own social media presence (LinkedIn and Twitter).

1.4 consortium

Pursue	Korn Recycling GmbH
Address	Under the Malesfelsen 35 - 45 72458 Albstadt www.korn-recycling.de
contact person (Contact details)	Wolfgang Kowalczyk Wolfgang.Kowalczyk@korn-recycling.de Tel.: 07431/94929-102 KORN
Skills	is a recycling company headquartered in Albstadt. The people of the Swabian Alb have always been known as particularly gifted tinkerers and inventors. Famous technology pioneers and engineers hail from this region. KORN operates one of Europe's most modern commercial waste sorting and alternative fuel processing plants. Its core competence lies in the disposal of waste from industrial, commercial, and retail businesses, as well as private households. Recycling and the utilization of waste are central to continuous innovation. Since 2002, KORN has been producing high-quality alternative fuels for the cement and power plant industries.
Project-specific References	• Industrially certified sorting facility for household and commercial waste • State-of-the-art commercial waste sorting & Alternative fuel processing plants (10 NIR sensors, 3 X-ray sorters, 3 ballistic separators, belt scale, etc.) • Certified waste disposal company • 75,000 tons of input per year for the Alternative fuel processing • Energy management according to ISO 50001:2018

Pursue	Polysecure GmbH
Address	St. Georgener Str. 19 79111 Freiburg www.polysecure.eu
contact person (Contact details)	Markus Reisacher, markus.reisacher@polysecure.eu Tel.: +49 761 5579 785 20
Skills	Polysecure is a specialist in marking and detection technologies, boasting an innovative technology platform that has been continuously expanding for 12 years. A particular focus is on fluorescent particles, which are already commercially available in ton-scale quantities for product authentication. These tracers can also be used for individual product tracking or, through our TBS-light or SORT4CIRCLE® sorting technologies, for the efficient and reliable sorting of material and waste streams into desired fractions. Polysecure's marking, detection, and sorting solutions are protected by approximately 30 patent families and are continuously developed and improved in collaboration with scientific (e.g., KIT) and strategic partners (e.g., ZEISS, Evonik, Röchling).
Project-specific References	• The interdisciplinary team's field of expertise includes, among other things, inorganic and organic chemistry, optical physics, plastics engineering, electronics, automation, and hardware and software development. solid-state Infrastructure: Chemistry laboratory (including relevant chemistry, wet chemistry, particle characterization), production infrastructure for tracer manufacturing on a ton scale, detection laboratory, plastics application laboratory, sorting pilot plant. TBS has been and is being established in several Baden-Württemberg locations. Further developed and enhanced through Württemberg, German, and European research projects: Tasteful, proViTASK, MaReK, CircularFoodPack • Polysecure developed a TBS process with and for REHAU to separate glass fiber-reinforced PVC flakes from standard PVC flakes. The first TBS flake sorting machine was built and industrially validated in the process.

Pursue	CARBOWEST GmbH
Address	Westring 10 59320 Ennigerloh
contact person (Contact details)	Dipl.-Ing. Olivier Inhoff oinhoff@carbwest.de Tel.: 02524 9307-0
Skills	CARBOWEST operates a direct oiling/liquefaction plant in Ennigerloh, Westphalia, based on the patented process. Carboliq technology. This plant can convert industrial waste into an ISCC+ certified petroleum substitute (CLR). The product is distributed via tanker trucks to refineries and the petrochemical industry.
Project-specific References	• BImSchG permit as a chemical-physical Treatment facility • Operation in a 3-shift system (24/7) since 2021, more than 20,000 operating hours • Processing of multilayer films, high-calorific alternative fuels, off-spec sorting fractions from sorting plants • Capacity: Input up to 1,500 t/a; Output up to 1,000 t/a • Confirmation of end-of-waste status • Certification of the company according to waste management regulations, ISO 9001 and ISCCplus; equipment according to AD2000 • Industrial framework conditions (real waste, world-Scale equipment • Qualification of waste according to RAL724, as Laboratory measurements of calorific value according to DIN 51900-3 - 2005-01

Pursue	carboliq GmbH
Address	Karlstraße 8b 42897 Remscheid
contact person (Contact details)	Dr.-Ing. Stephan Aschauer Saschauer@carboliq.com Tel.: +49 176 24724579
Skills	Carboliq is the technology company that develops, recycles and commercializes the technology for liquefying mixed plastic waste from various sources. Sources
Project-specific References	• Process engineering development • Three patents for the liquefaction of plastic waste • Business cases • In-depth market knowledge • Scale-up Fluid dynamics Process design • Plant operation • Quality management according to ISO 9001 • Offtake agreements with refinery and petrochemical company

	Marc König Management Consulting
Address	Wilhelm-Schickard-Straße 9 76131 Karlsruhe www.marckoenig.info
contact person (Contact details)	Dr. Marc König beratung@marckoenig.info
Skills	Marc König Management Consulting is an owner-managed consultancy specializing in supporting deep-tech companies. Its focus is on assisting with product development, supporting companies with financing and grants, conducting customer acceptance research, and developing business concepts. This support is based on a specific approach developed by Dr. Marc König for rapidly growing SMEs.
Project-specific References	Dr. Marc König has successfully completed over 50 R&D projects at the state, federal, and EU levels. He has also analyzed over 1,200 business plans and published the key insights in more than 15 international publications. Dr. König is currently focusing on sustainable business concepts within the circular economy. He holds, among other qualifications, a UNESCO-certified ethics certificate for sustainability.

1.5 Work plan (project structure, tasks and work packages)

AP	Work Package / Months 1-18	2024				2025				PM grain	PM Poly-secure	PM Carbo-west	PM Carbo-liq
		Q1	Q2	Q3	Q4	Q1	Q2						
1.	Requirements analysis		M1							1.80	1.00	0.00	0.00
2	Detailed concept of the sorting and recycling process			M2						2.70	1.50	0.00	0.00
3	Development of sorting technologies for alternative fuels and PA-containing multilayer films				M3					7.80	12.00	0.00	0.00
4	Qualification and Pre-sorting of EBS and PA Films on the industrial					M4				13.20	8.50	0.00	0.60
5	Grain plant Plant tour with pre-packaged grain-EBS++ at Carbowest						M5			0.00	0.00	8.10	9.90
6	Evaluation of the results and Investment planning							M6		0.90	1.00	0.00	0.50
7	Project Management & communication of Results in relevant									1.80	2.00	0.00	0.45
	Target groups												
	Total PM									28.20	26.00	8.10	11.45

Milestones: • **MS**

1: Tasks in MS1 (end of February 2024): Requirements document

• **MS 2:** Tasks in MS2 (end of May 2024): Concept for the Close Loop Process

- **MS 3:** Tasks in MS3 (end of October 2024): Documentation of results, waste stream and sorting concept for grain plant for the recovery of EBS++
- **MS 4:** Tasks in MS4 (end of October 2024): Qualification results documentation
 - Production of up to 20 tons of EBS++; sorting of up to 20 tons of multilayer Slides
- **MS 5:** Tasks in MS5 (end of March 2025): Results report on the output from the Direct liquefaction of EBS++
- **MS 6:** Tasks in MS6 (end of June 2025): Business concept & investment analysis

2. Analysis of the initial situation and existing requirements

2.1 Analysis of input material flows

Initially, a current state analysis was conducted. For this purpose, the CARBOWEST specifications were used (see Table 1). In addition, the Korn plant was inspected and the plant flow diagrams were studied. The existing EBS (recycled fuel waste) from Korn had to be analyzed. Based on these results, six sampling points were defined at the Korn EBS plant. Samples were collected at these points once a month for five months and sent to CARBOWEST for analysis. These samples are listed in Table 1.

The following physical properties were tested in the laboratory: calorific value, moisture content, ash content, and chlorine content.

Table 1 Specifications CARBOWEST

Designation	Unit	min.	max.
Calorific value	MJ/kg	24	
Calorific value (TS)	MJ/kg	23	
sieve size	mm	30	
bulk density	kg/m ³	80	
Ceramics, stones, porcelain	Mass-%		< 0.1
Glass	Mass-%		< 0.1
FE metals	Mass-%		< 0.1
non-ferrous metals	Mass-%		< 0.1
Wood	Mass-%		< 0.1
rubber	Mass-%		< 0.1
Polyurethane (PU, foam) mass %			< 0.1
chlorine	Mass-%		<0.4
fluorine	Mass-%		<0.01
Biogenic component	Mass-%		20
Ash content	Mass-%		10
Water content	Mass-%		10

Calorific value: It is used to check how high the plastic content in the material is; the higher the calorific value, the higher the plastic content.

Moisture: The material must be as dry as possible when introduced into the CARBOWEST system.

Excessive moisture content increases byproducts, and water or steam can damage system components.

Ash: The ash content (inert content) is a measure of how much non-liquefiable material is present. If this value exceeds a certain threshold, the process becomes less economical because more byproducts are generated, which would have to be accepted and disposed of by the customer.

Chlorine content: It should be kept low, as chlorine can lead to corrosion in the plant and also ends up in the petroleum substitute product, which does not meet the specifications of the petrochemical industry.

Additional requirements from CARBOWEST were that the high proportion of aluminum, dust, copper and ceramic in the EBS had to be reduced.

2.1.1 Sample analysis at CARBOWEST

The previously defined samples were collected by KORN over a period of five months and sent to CARBOWEST for further analysis (results see Table 2) to obtain a temporal overview of the material flow behavior. This long-term collection ensured that as many different samples as possible were included in the analysis, since the composition of waste is highly dependent on the season. For example, the waste generated in June differs from that generated in November, which is reflected in the quality of the RDF.

Below are some example images (Figure 3 to Figure 8) of the samples.
how they arrived at CARBOWEST:



Figure 3 Sample F1.2/F2.2



Figure 4 Sample G1



Figure 5 Sample F2.1



Figure 6 Sample F2.4

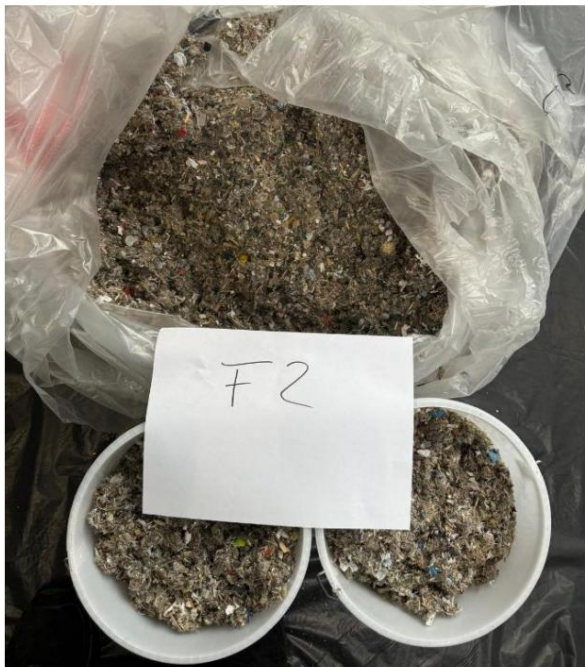


Figure 7 Sample F2



Figure 8 Sample F1.1

The samples were analyzed in the laboratory at the CARBOWEST site of Ecowest. The following illustration shows the procedure:

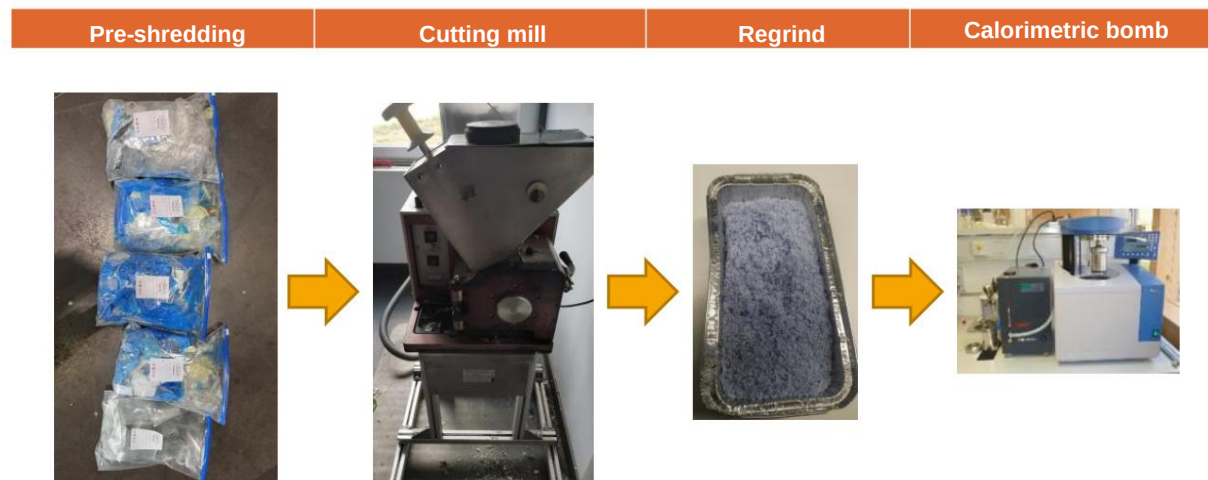


Figure 9 Sampling and sample preparation for determining calorific value, ash and Water content

Table 2 shows that the F2 fractions are well suited for further processing and further sorting / reprocessing.

Table 2: Monthly overview of samples from KORN from June to November 2024

		Moisture in OS	Cutting capacity	Calorific value	Ash content OS	Chlorine content in OS
		%	-	MJ/kg	% %	
		1...15	good - bad,	24...40	max. 10	0.4
F1.2; F2.2	June	8.8	average	27.4	10	2.51
	July	12.58	medium	20.2	26	0.12
	Aug	6.59	medium	24	22	-
	September	7.06	medium	18.5	25	0.66
	Nov	9.15	too coarse for mill	-	-	-
	O	8,836	medium	22.53	20.75	1.10
G1	June	16.02	medium	18.6	3	0.21
	July					
	Aug	12.11	medium	16.1	1	-
	September	16.82	medium	18.7	17	1.03
	Nov	17.5	bad	18.2	6.00	-
	O	15.6	medium	17.90	6.75	0.62
F2.1	June	10.36	medium	17.4	31	1.8
	July	12.44	medium	19.8	4	0.12
	Aug	4.17	medium	23.5	10	-
	September	5.79	medium	21.7	35	1.69
	Nov	4.21	good	23	23	-
	O	7.4	medium	21.08	20.60	1.20
F2.4	June	21.71	medium	19.7	10	0.63
	July	18.9	medium	18.9	15	0.14
	Aug	4.73	medium	24.2	2	-
	September	13.24	medium	30.5	11	0.36
	Nov	17.96	good	23.3	10	-
	O	15.31	medium	23.32	9.60	0.38
F2	June	13.83	good	22.3	18	0.47
	July	9.78	good	24.2	11	1.28
	Aug	6.25	good	25.5	13	-
	September	0.76	good	27.2	8	0.26
	Nov	13.6	good good	21.9	18	-
	O	8.8	good	24.22	13.60	0.67
F1.1	June	24.19	good	18	24	0.33
	July	21.99	good	18.7	24	0.49
	Aug	22.98	good	16.8	24	-
	September	16.03	good	21.2	3	1.43
	Nov	20.59	good good	16.9	23	-
	O	21.2	good	18.32	19.60	0.75

3 Development of the detailed concept for the sorting and recycling processes

3.1 Introduction

The goal was to provide a high-calorific-value, low-contaminant refuse-derived fuel (RDF++) that is particularly suitable for chemical recycling processes. Polyolefins – especially PE films, HDPE, and PP – represent attractive target polymers in this context. Simultaneously, minimizing undesirable substances such as PVC (chlorine carrier), fluorinated plastics, inert materials (e.g., glass, ceramics), metals, and biogenic components is essential. Only through precise and adaptable process control can the required product qualities and specifications from the patented carboliq process be achieved. Key control parameters include process-related specifications and measurable quality and process KPIs.

A comparison of the measured values of the current alternative fuel (EBS) and the specified target values revealed deviations. These were analyzed, and alternative production processes and courses of action were developed based on this analysis.

3.2 Derivation of process specifications

3.2.1 Material preparation

The processing begins with the loose commercial waste fraction. The first step involves pre-shredding, with the aim of achieving a specific particle size distribution.

Subsequently, a fine fraction <10–20 mm was separated by sieving. This fraction typically contained high levels of dust and inert materials and was removed from the process. The downstream 2D/3D separation is performed using a ballistic separator.

3.2.2 NIR sorting

The sorted fraction was separated according to polymer composition using near-infrared (NIR) sensors. It is crucial that the discharge control is optimized to minimize any incorrect sorting.

3.2.3 X-ray sorting

Mineral sorting was ensured using X-ray equipment, which provides information about the density and chemical composition of the material and thus reliably separated minerals from the material stream.

3.2.4 FE and NE separators

To reduce contaminants, metallic components were removed using ferrous and non-ferrous metal separators.

3.3 Relevant Key Performance Indicators (KPIs)

3.3.1 Quality KPIs

The most important quality indicators (KPIs) for evaluating the EBS++ product included:

- PVC/Chlorine: < 0.4 m-%
- Fluorinated plastics: < 0.01 wt%
- Total inert materials: $\leq$ 0.5 wt% (per component < 0.1 wt%)
- FE/NE metals: each < 0.1 m-%
- Ash content: $\leq$ 10 m-%
- Water content: $\leq$ 10 m-% (operationally < 5%)
- Biogenic components: $\leq$ 20%

- Calorific value: $\approx$ 24 MJ/kg

3.3.2 Process KPIs

The monitoring of operating parameters was carried out using the following process KPIs:

- Band occupancy: 60 to 80%
- Monolayer rate: > 85%
- Regular calibration of blow time and delay
- Daily cleaning of cameras and lighting units
- Monitoring of nozzle pitch, compressed air control and object detection

3.4 Development of a detailed concept

3.4.1 Process line management for commercial waste

After numerous trials with different NIR settings and determining which materials resulted in negative rejection, an optimal process line design was developed.

3.4.2 Quality Assurance

Quality assurance is an integral part of the operation. A representative 1 kg sample was analyzed per shift. Daily laboratory analyses were performed to determine the calorific value, chlorine content, and water and ash content. In addition, these in-house analyses were supplemented weekly by external laboratory tests examining heavy metals.

3.4.3 Evaluation of Results

The chosen combination of ballistic separation, optimized NIR parameterization, and metallic and fine-grained separation ensured a high yield of pure polyolefins while simultaneously complying with all limit values. The target calorific value of $\approx$ 24 MJ/kg was thus achieved. The moisture content is highly dependent on the season. Consideration is being given to the extent to which pre-drying can be integrated to ensure consistent compliance with the limit values.

3.4.4 Conclusion

The combination of process-specific adjustments, a defined KPI structure, and continuous quality assurance ensures the process stability and product quality of a high-quality EBS++ from mixed commercial waste.

4 Validation of the TBS-Light technology for the precise sorting of marked composite packaging and validation of the SORT4CIRCLE Technology as an alternative solution for the specific sorting of Commercial waste and other waste streams, generating a new EBS++ product

4.1 Strand A: Sort4Circle

4.1.1 Motivation

The liquefaction process places certain minimum demands on the quality of the input material, which must be met for a technically stable process. In particular, the chlorine content of the material and the proportion of inert materials are relevant. When using RDF as a feedstock, compliance with these minimum requirements is a particular challenge due to the high heterogeneity of the material stream. The composition of the material can vary considerably over time – depending on the source of the waste – and pre-sorting may not always be able to remove chlorine-containing plastics and inert materials from the stream with sufficient efficiency to guarantee the purity required for liquefaction. Therefore, the experiments described below should investigate the nature of the remaining impurities in the RDF material stream and whether additional (or alternative) sorting using the Sort4Circle process can produce a better input material for the liquefaction process and identify pure materials that could be directly processed mechanically.

4.1.2 Experimental Objectives

Material samples were taken from the sorting plant at Korn Recycling over a period of four months and subsequently sorted again at the Sort4Circle pilot plant at Polysecure. The sorting trials were conducted with the following objectives:

1. an overview of the composition of the material flow and its
To win over fluctuations
2. the sorting efficiency of the existing measurement technology for the commercial waste stream
characterize
3. To recognize special features and special cases of objects occurring in the material flow, and to identify
necessary improvements and extensions of the measurement technology with regard to the specific
requirements of the material.
4. Implement any identified extensions and test them directly.

The experiments were conducted with a focus on the level of the individual object in order to investigate specific relationships between object properties and the measurement signal and to gain a precise understanding of the measurement and analysis requirements for these objects. The aim of the experiments was not to obtain representative statistics on the material composition in the grain sorting plant or to conduct a field trial in a typical industrial environment.

4.1.3 Experimental material

Samples were taken from two selected points in the grain processing plant, each providing different specifications. This stream has already undergone pre-processing (pre-crusher, ballistic separator, ferrous metal separation, vibrosifter/zigzag classifier) but has not yet been fully milled. As a result, the material contains parts of the rolling/heavy fraction. These were coarsely crushed by the pre-crusher (to <250 mm), although small particles often remain intact. Fraction F1.2 contains larger particles in the size range of 85 to 250 mm, while fraction F2.2 contains smaller particles in the range of 20 to 85 mm.

4.1.4 Principle of the Sort4Circle process

The Sort4Circle® process developed by Polysecure is based on the fundamental idea of improving the purity and yield achievable in sorting processes by optimizing the properties of the material being processed.

The previously most commonly used cascade sorting method for waste sorting (one sorting stage per rejected fraction) has been replaced by single-object sorting. In cascade sorting, a single fraction was identified and rejected at each sorting stage. Therefore, a separate detection system, a pneumatic nozzle strip for blowing out the waste, and the associated control system were required for each fraction.

This process scales poorly with an increasing number of fractions, thus hindering the most complete possible separation of waste streams into different recycle specifications. in

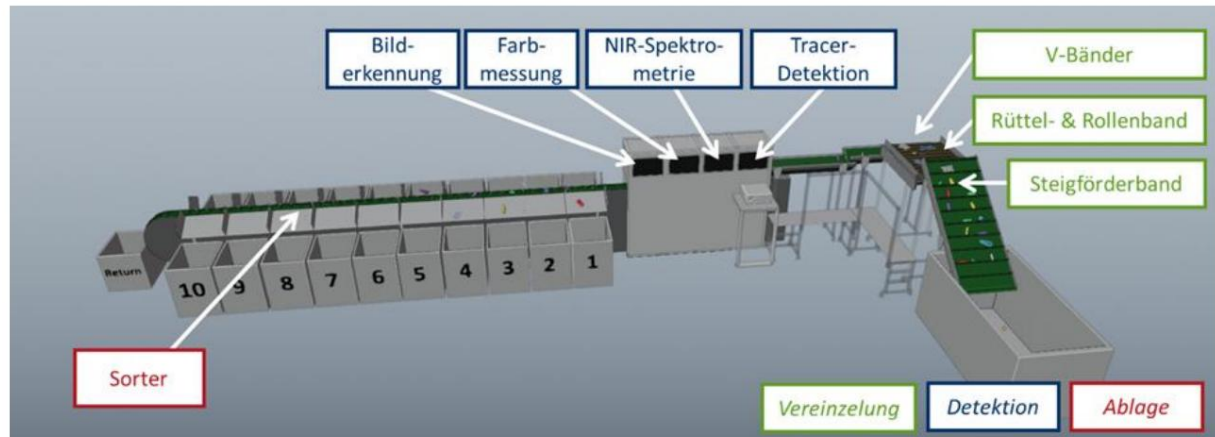


Figure 12: Schematic diagram of a Sort4Circle® system consisting of singulation section, detection chambers and storage device

The S4C process instead begins with a one-time separation (single-object separation). From this point on, the position of each object can then be tracked separately.

All necessary measurements are carried out on each object one after the other, e.g.

Near-infrared spectroscopy, colorimetry, AI-assisted object recognition, barcode reading, LIBS, etc. Optionally, Polysecure's tracer-based sorting technology (marking with fluorescent marker particles) can also be used to differentiate specifications that are otherwise unmeasurable. The combination of different measurement methods can be used in this system to obtain additional information. Finally, the object is deposited in a controlled manner at a designated location according to the fraction determined from the measurement results.

The mechanical design of the singulation line must be adapted to a certain extent to the specific material flow (size range, weight, shape) in order to achieve an optimal singulation rate. Any remaining singulation errors can be identified based on the detection results, and the parts can be returned or sorted out.

4.1.5 Design and properties of the S4C test facility

The experimental setup used for the trials in this project is located in Polysecure's pilot plant and serves to demonstrate combined detection using NIR spectroscopy and marker code measurement. It thus represents the central part of a complete S4C system.

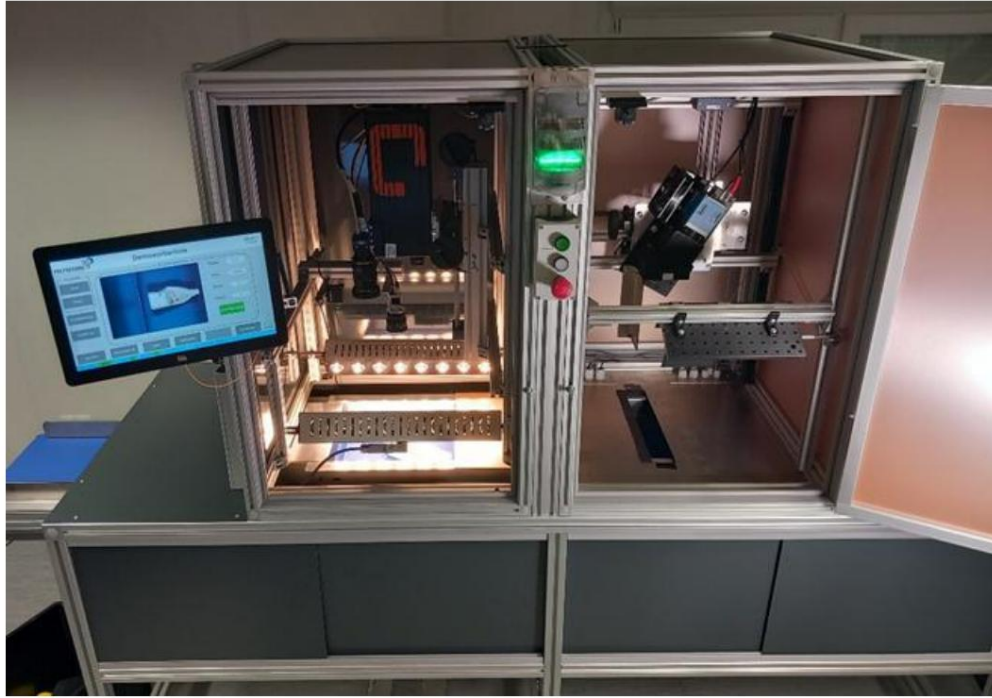


Figure 13: Detection chambers of the S4C test setup. Left: VIS and NIR chamber, right: Marker detection (not used in the experiment)



Figure 14: Setup of the storage containers for the sorting trials. In the center of the image is the end of the conveyor belt for collecting the detected parts. The parts are fed in at the opposite side.

Above a conveyor belt with mounted cleats are two measuring chambers: The first chamber contains a halogen illumination unit, a color camera, and a NIR hyperspectral camera for recording reflection spectra. This measuring system is used to identify polymer types. The second chamber contains an infrared laser for exciting the markers and a sensitive optical detector system for the characteristic fluorescence emission. For the following experiments, only the first chamber was used.

The objects to be measured are placed individually into a compartment of the conveyor belt. After pressing the button for individual measurement on the user interface, the

The object is transported through both chambers, the measurement results are displayed, and the part can be removed at the other end and placed accordingly. In addition to the final result (the identified polymer type), the results display also includes an image of the object and, for internal evaluation, various spatially resolved information on detection accuracy and other criteria (Figure 15).

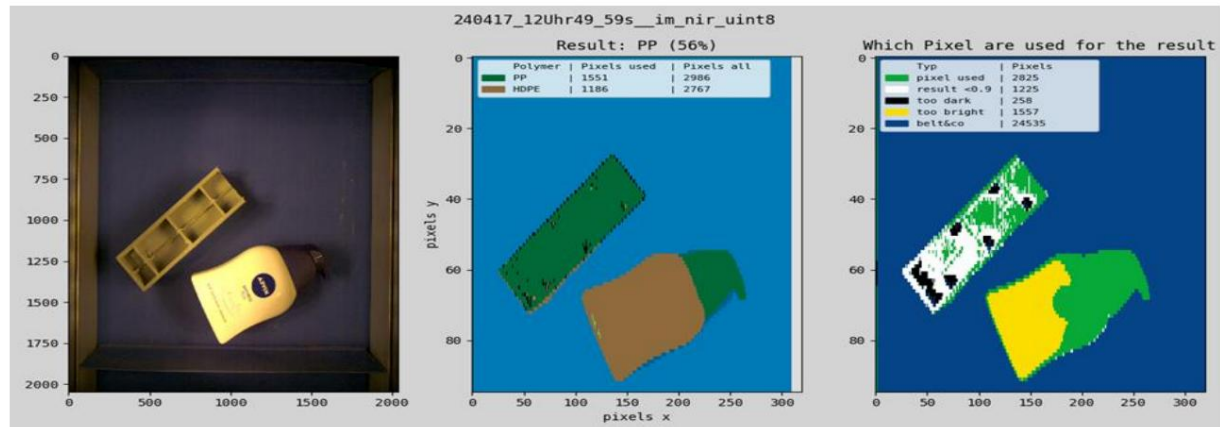


Figure 15: Depiction of the analysis screen of the test setup. Left: Photo of the measuring chamber, center: Classification result of the NIR measurement, right: Display of characteristic values for detection quality.

This additional information can, for example, provide clues about the actual material composition of objects classified as "not recognized" and be used for manual classification.

4.1.6 Measurement campaigns

4.1.6.1 Run 1

The sorting algorithm, in the version used in this run, recognizes 12 polymers (see Table 4 for the list). For the trials at RohWerKBaWü, the material classes wood and wood-based materials, as well as paper, were also added to the algorithm. Additionally, the fractions "ceramics, stone, concrete", "metals", and "mixed materials/other" were defined.

However, ceramic materials and metals cannot be measured using NIR technology due to the nature of the technology and were therefore identified by visual inspection during manual sorting. Black objects, which usually contain soot, are also undetectable in the NIR range. Therefore, a fraction of objects "too dark/not measurable" also exists.

The sorting process was as follows:

1. Evaluation of the sorting system results. If the result was clear, the sorting was carried out accordingly. If the result was "too dark," the material was placed in the "too dark" fraction.
2. If the system correctly identified multiple polymers in a plastic object, it was processed in The "Mixed Materials/Other" category was filed.
3. If the algorithm did not produce a result, e.g., due to a material that was not part of the program or a signal that could not be evaluated, the material was identified visually whenever possible. This was always the case, especially with metals and ceramic materials.
4. If a reliable result could not be determined in any way, or if the object consisted of several different materials (to a non-negligible extent) or partly of indeterminate components, it was assigned to the "mixed materials/other" category.

Each result obtained, including the source of the information and any notes about the object, was recorded. All measurement data and images were saved for future analysis.

After sorting, the resulting fractions were weighed, and the liquefiable fractions were sent to the project partner carbolig for further laboratory analysis. The results are shown in Table 4. Chlorine and chlorine were defined as non-liquefiable.

Fluorine-containing plastics PVC, PVDF and PTFE, as well as all non-plastic fractions and material mixtures. Figure 16 shows the sorted material separated into good and bad fractions according to this rule.

A total of 21.9 kg of material from F1.2 and 5.6 kg from F2.2 were sorted.



Figure 16: Sorted material from Run 1. a) F1.2, Good fractions, b) F1.2, Bad fractions, c) F2.2, Good fractions, d) F2.2 Bad fractions

Table 4: Mass distribution of the sorted fractions, Run 1. The fractions marked in green were classified as suitable for liquefaction.

	F1.2 (large)		F2.2 (small)	
fraction	Mass / kg proportion		Mass / kg proportion	
PP	0.28	1%	0.176	3%
PE	0.16	1%	0.134	2%
PET	0	0%	0.057	1%
PVC	0	0%	0.162	3%
PVDF	0	0%	0.018	0%
PC	0.12	1%	0	0%
PA	0.06	0%	0.065	1%
PEEK	0	0%	0	0%
PS	0.2	1%	0.063	1%
PMMA	0	0%	0.019	0%
PTFE	0	0%	0	0%
POM	0	0%	0	0%
too dark/not measurable 0.82		4%	0.261	5%
Wood	10.1	46%	1,629	29%
Paper/Cardboard	1.56	7%	0.126	2%
Ceramic/stone/concrete	3.3	15%	1,192	21%
metals	0.14	1%	0.213	4%
Mixed materials/Other it	5.16	24%	1,486	27%
sum	21.9	100%	5,601	100%

The proportion of recyclable plastics in the material was very low, at approximately 4% (F1.2) and 8% (F2.2). Many plastic fractions were only partially filled or not filled at all. Therefore, the statistics are insufficient for reliable conclusions regarding the plastic content. By far the largest share consisted of wood and wood-based materials at 46% and 29%, respectively, followed by the "mixed materials/other" fraction (24% and 27%). Ceramics, stone, and concrete comprise a relatively large mass fraction simply due to their high density.

A significant portion of the "Mixed Materials/Other" fraction consisted of large spools of yarn, which were very numerous in this batch. The yarn was identified as PET, the spool as paper. Many pieces of wood and particleboard were also contaminated with other materials such as gauze, plastic threads, polystyrene, or foam and were therefore classified as "Other." Such material mixtures can, in principle, also be classified as liquefiable material and would not necessarily have to be sorted out. To reflect this, the fraction definitions were adjusted in Run 2.

4.1.6.2 Run 2

The sorting process was the same as in Run 1, however, changes were made to the algorithm and the definition of the factions. Generally, more value was placed on the sorting.

The focus was on increasing the proportion of liquefiable material, and a higher degree of impurities was accepted. Thus, parts with low levels of inert materials or small metal content (e.g., individual screws) were more likely to be classified as good material than as mixed material.

The algorithm has been further developed. The new version detects 13 polymers.

ABS and PUR were newly added, while PTFE was removed due to insufficient detection quality. PTFE was not present in Run 1.

Two new disposal fractions have been defined: "Plastic mixtures" and "Other material mixtures, liquefiable." The previous "Material mixtures/Other" fraction has been restricted to parts that cannot be assigned to any other fraction and is designated "Residuals." This change should make it possible to separate recyclable parts made of several types of plastic or other identifiable liquefiable components (e.g.,

Bitumen/roofing felt) were made accessible for liquefaction instead of being assigned to the sorted residual fraction. This had occurred several times during Run 1. Objects with unidentifiable plastic components continued to be sorted into "Residual" to exclude contamination of the good fractions with PVC or PVDF. Additionally, a small supplementary fraction, "Sorted for Storage," was defined to allow and document the removal of individual, particularly interesting or special parts for later analysis.

Unidentified cases were evaluated more thoroughly than before. In cases of low-confidence analysis results that still showed a clear match to a material, the result was manually checked for plausibility. This involved considering the visual and tactile appearance, as well as any embossed or printed material markings. If the result was plausible, the object was placed in the identified fraction; otherwise, it was placed under "Remainder." The sorted material is shown in Figure 17, and the sorting results are in Table 5.

In Run 2, only the large input fraction (F1.2) was sorted, but a larger quantity of 48.9 kg.

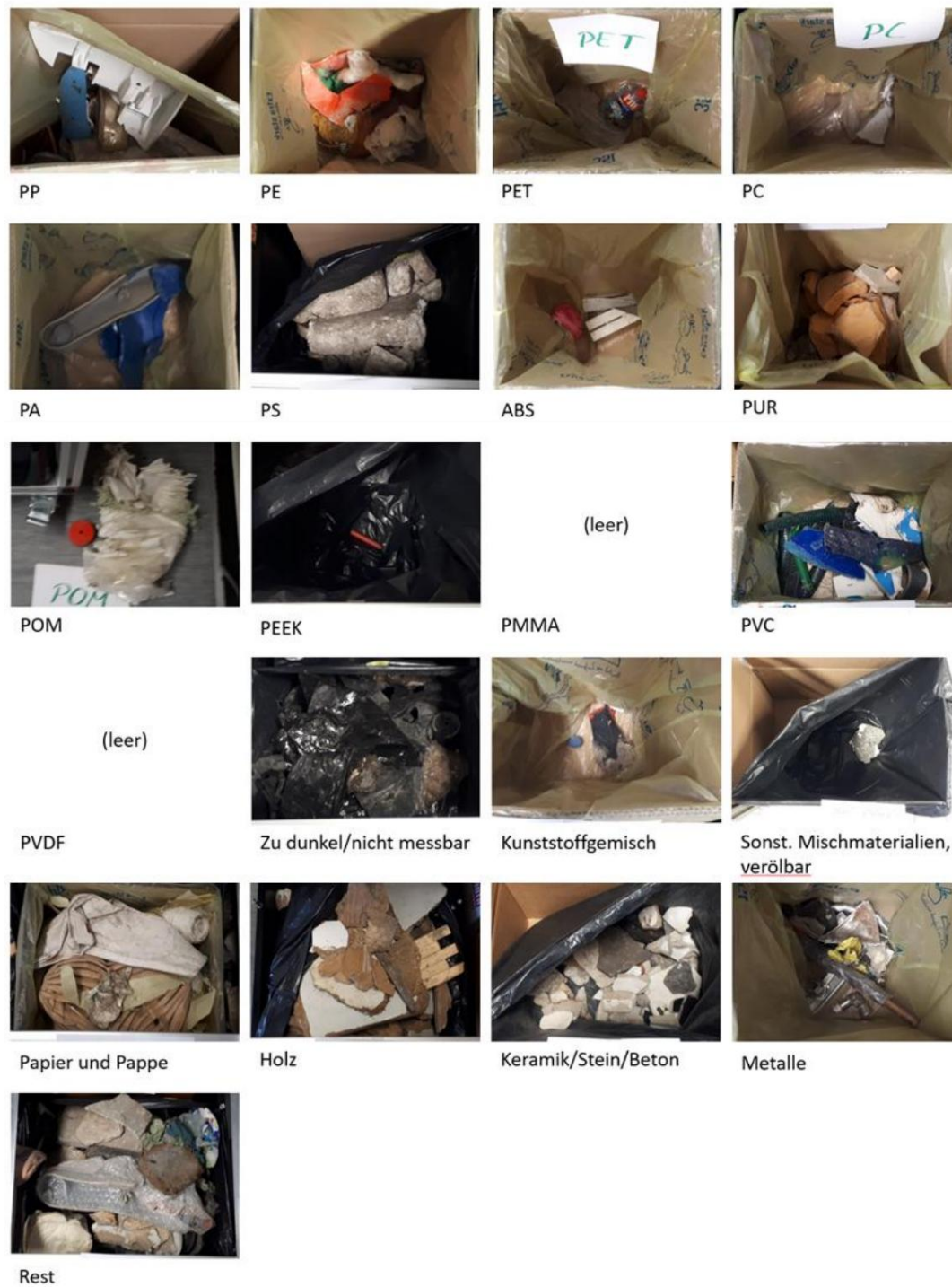


Figure 17: Sorted fractions from Run 2

Table 5: Number and mass distribution of the sorted fractions, Run 2.

fraction	F1.2 (large)			
	Number	Share	Mass / g	Proportion mass
PP	23	4%	2,670	5%
PE	12	2%	490	1%
PET	2	0%	95	0%
PC	3	1%	344	1%
PA	4	1%	304	1%
PS	36	7%	1,206	2%
ABS	4	1%	169	0%
PURE	18	3%	1,784	4%
POM	2	0%	370	1%
PEEK	1	0%	9	0%
PMMA	0	0%	0	0%
PVC	13	3%	747	2%
PVDF	0	0%	0	0%
to dark/not measurable	99	19%	10,640	22%
Plastic mixture. Other	3	1%	88	0%
material mixture, liquefiable.	1	0%	67	0%
Wood	113	22%	10,820	22%
Paper/Cardboard	57	11%	3,760	8%
Ceramic/stone/concrete	38	7%	5,820	12%
metals	12	2%	1,041	2%
rest	69	13%	8,120	17%
Sorted out to storage	6	1%	398	1%
sum	514	100%*	48,942	100%*

*

Deviations from the sum of the individual items are shown on due to rounding errors

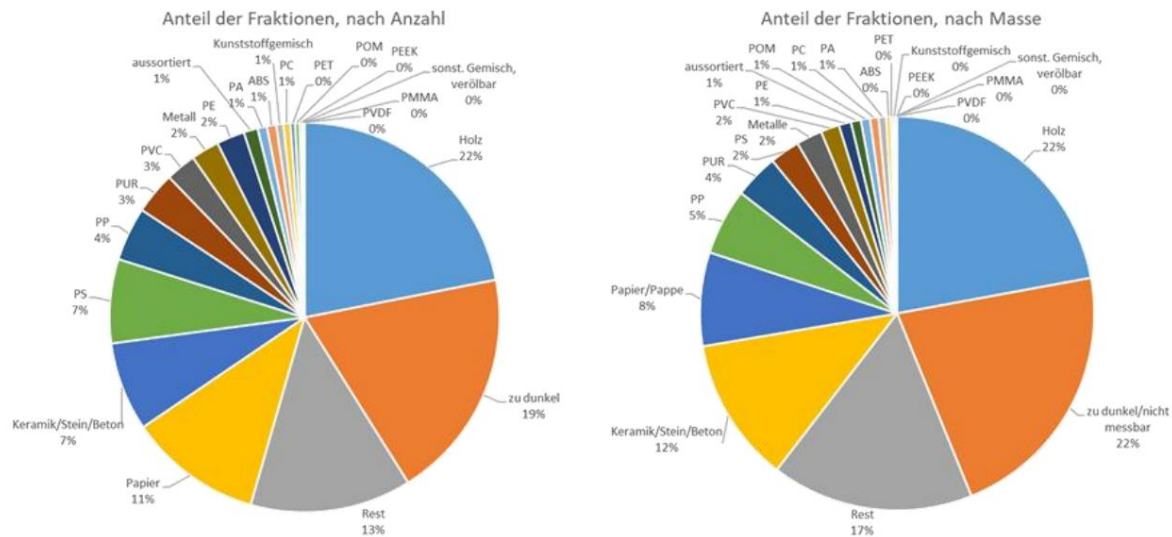


Figure 18: Proportions of the sorted fractions by number and mass, Run 2

The results were evaluated according to number and mass fraction, revealing slight shifts because the ceramic/stone/concrete fraction contains pieces with a significantly higher density than the other fractions. The opposite effect is observed for polystyrene (primarily foam boards).

Wood again makes up the largest share, closely followed by black materials and other non-measurable materials. The wood and paper fractions (generally pulp-based materials) exhibit a quasi-continuous scale along fiber size, ranging from paper through cardboard, fine fiberboard, coarse fiberboard, particleboard, to solid wood. Therefore, separating them into paper and wood is somewhat arbitrary. The implemented separation proved suitable in many cases, but in the "middle" of the scale it is still too inconsistent and thus in need of improvement. The question arises whether the separation should instead be optimized so that only paper and cardboard fall under "paper" and everything else under "wood-based materials," allowing the paper fraction to be sent for high-quality paper recycling.

Given the high proportion of black objects, including many potentially recyclable mono-material plastic parts, it is desirable to be able to sort this fraction as well. Since NIR technology reaches its physical limits here, the project focused on further developing mid-infrared reflection spectroscopy, which enables the identification of some polymer types in black objects (see section 4.1.8).

The newly defined fractions "plastic mixtures" and "other liquefiable material mixtures" were hardly used, as this batch, unlike the previous one, contained very few such "pure" mixtures. Most potentially suitable parts were contaminated with non-liquefiable components such as metal and were therefore disposed of as "residue".

The remaining fraction contained a correspondingly high proportion of plastic. Some of this could be recovered by shredding it into smaller pieces and re-sorting, but for reasonable cost-effectiveness, a small parts sorter optimized for bulk materials would be necessary.

The investigation revealed several new starting points for improvements to the sorting algorithm. For example, some targets are not yet perfectly matched, which manifests itself in more frequent low match values for certain polymers. In the decision tree, the interplay of the thresholds for "too dark/not measurable," confidence, number of evaluable pixels, and number of detected material clusters can be further optimized.

The proportion of liquefiable plastic fractions in this batch was 15% (by mass). This material was forwarded to carbolig.

4.1.6.3 Run 3

In this sorting test, both fractions F1.2 and F2.2 were sorted again, with the larger fraction comprising only 13.9 kg. A total of 1000 pieces, or 20.6 kg, of the smaller fraction were sorted.

The sorting strategy from the previous run was retained. The "Plastic Mixtures" fraction was also used to store some mono-material objects made of untrained plastic types for which no separate fraction had been defined. These were individual objects made of MABS and PBT.

Table 6: Number and distributions based on the number and mass of the sorted fractions, Run 3

	F1.2 (large)				F2.2 (small)			
fraction	Number	Share Number	Mass / g	Portion mass	Number	Share Number	Mass / g	Portion mass
ABS	20	19.6%	5340	38.4%	35	3.5%	1284	6.2%
18 dark/not measurable up to		17.6%	2505	18.0%	181	18.1%	6280	30.5%
Ceramic/stone/bed on	12	11.8%	2162	15.5%	49	4.9%	3384	16.4%
rest	15	14.7%	1227	8.8%	89	8.9%	1219	5.9%
Wood	9	8.8%	1032	7.4%	309	30.9%	4635	22.5%
PS	11	10.8%	419	3.0%	105	10.5%	694	3.4%
Plastic mixture 3		2.9%	390	2.8%	22	2.2%	391	1.9%
Sorted out storage 3 to		2.9%	260	1.9%	6	0.6%	344	1.7%
PET	2	2.0%	141	1.0%	21	2.1%	325	1.6%
PP	2	2.0%	123	0.9%	31	3.1%	367	1.8%
PE	3	2.9%	117	0.8%	57	5.7%	330	1.6%
other mixture, 2 liquefiable		2.0%	98	0.7%	10	1.0%	243	1.2%
Paper/Cardboard	1	1.0%	77	0.6%	5	0.5%	114	0.6%
PVC	1	1.0%	27	0.2%	57	5.7%	670	3.3%
PURE	0	0.0%	0	0.0%	2	0.2%	30	0.1%
metals	0	0.0%	0	0.0%	6	0.6%	47	0.2%
POM	0	0.0%	0	0.0%	1	0.1%	37	0.2%
PC	0	0.0%	0	0.0%	3	0.3%	35	0.2%
PA	0	0.0%	0	0.0%	7	0.7%	124	0.6%
PEEK	0	0.0%	0	0.0%	0	0.0%	0	0.0%
PVDF	0	0.0%	0	0.0%	0	0.0%	0	0.0%
PMMA	0	0.0%	0	0.0%	4	0.4%	29	0.1%
sum	102	100%*	13,918	100%*	1,000	100%*	20,582	100%*

*

Discrepancies with the sum of the individual items are due to rounding errors.

In this experiment, ABS constituted the largest fraction by mass in the large input fraction F1.2 (Table 6). Most of the ABS parts were solid blocks, possibly casting or extrusion remnants from the injection molding of ABS parts or from 3D printing. Therefore, the mass fraction of liquefiable materials was very high this time, at 47.6%. In F2.2, these blocks were practically absent, so the distribution more closely followed the previous pattern. The mass fraction of liquefiable materials was 18.9%.

This demonstrates a large variance in the commercial waste stream and a potentially significant dependence of material quality during liquefaction from batch to batch. High-quality sorting into multiple fractions can compensate for this effect, as it enables the controlled mixing of the input fractions in constant ratios and thus the balancing of variable compositions of the input material over a longer period.

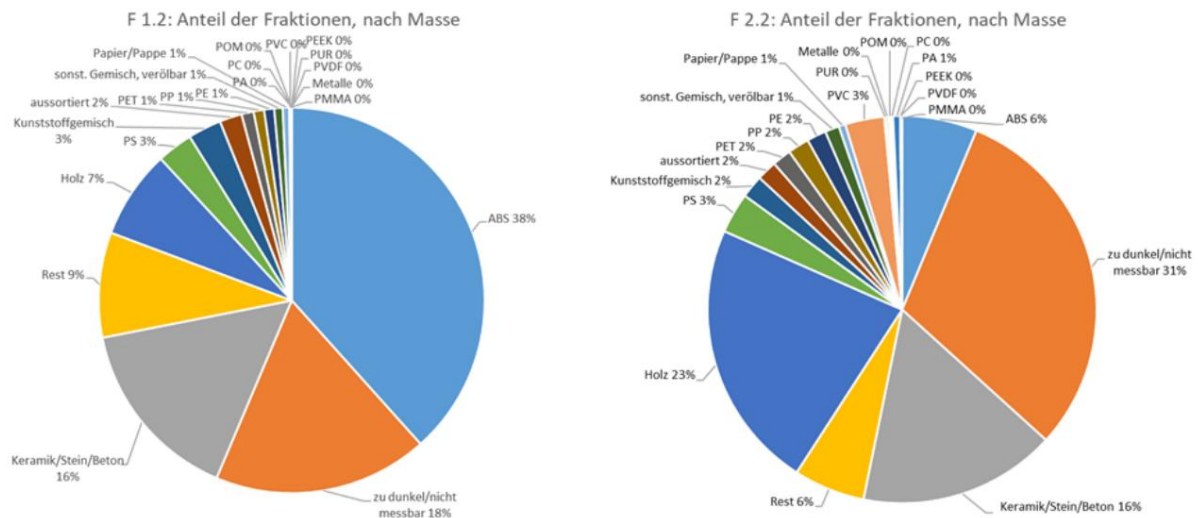


Figure 19: Mass fractions of the sorted fractions for F1.2 and F2.2, Run 3

The experiment provided new impetus for the further development of measurement technology: Two types of plastic – MABS and PBT – were present that had not previously been included in the system. MABS was not recognized as ABS, making the creation of a new MABS target possible. Due to the strong similarity, PBT was recognized as PET. Whether a differentiation is possible using measurement technology remains to be investigated. Furthermore, some cork objects (floor tiles) were present in the stream. Despite its similarity to wood, cork was not recognized as such, so the generation of a specific cork target also seems feasible here. This would enable the sorting and collection of this valuable natural material.

4.1.7 Results Analysis

Table 7 summarizes the detailed results from the measurement campaigns with regard to the suitability of the material for liquefaction. Two properties play a dominant role here: the mass fraction of the material suitable for liquefaction, and the mass fraction of the material interfering with liquefaction, especially substances containing chlorine and fluorine.

The latter must absolutely be removed from the material flow.

Table 7 clearly shows two facts, in addition to the high variation in the proportions in the different batches, which suggests the need for homogenization of the material flows:

- The goal of pre-sorting, to reduce the proportion of Cl- and F-containing substances in the material stream to well below 2%, is achieved on average, but not for every characterized batch. Particularly in the small rolling fraction (F1.2), more chlorine-containing materials (the fluorine content is generally very low) are found than desired. This clearly demonstrates that purer sorting and, above all, improved detection of chlorine-containing materials can increase the efficiency of liquefaction. Sort4Circle can achieve this.
- The mass fraction of the material classified as too dark by the NIR system is similar to the mass fraction of the liquefiable fraction. Since this fraction apparently consists largely of plastics, it would be important for the economic viability of liquefaction to specifically utilize this mass potential.

This requires a measuring technique capable of detecting black plastics. Section 3.1.8 deals with the development of this measuring technique.

Table 7: Summary of the main results from the measurement campaigns

		F1.2 (large)		F1.2 (small)	
	Run 1	Run 2	Run 3	Run 1	Run 3
Liquefiable 4%		15%	48%	8%	19%
Contains CI and F 0%		2%	0.2%	3%	3%
Too dark/not measurable 4%		22%	18%	5%	31%

During the measurement campaigns, the existing NIR measurement technology was extended to include the fractions wood, cardboard/carton, and additional plastic fractions that frequently occur in the material stream. However, significant material fractions remain in the analyzed samples. These are streams that cannot be detected using NIR sensors. Besides the black plastics mentioned above, these are primarily metallic materials and objects made of ceramic, stone, or concrete. The small but significant presence of metal is particularly surprising, as effective separation methods exist for it. Therefore, to obtain a stream of liquefiable materials, it is necessary to sort them positively. The non-liquefiable materials remain in the residue and can be disposed of separately.

In the last run with the optimized NIR measurement system, 50% of the large and 60% of the small objects in the material streams were detected. Comparing these percentages to the maximum number of objects that could be detected by the NIR measurement technology (53% for the large object stream, 67% for the small object stream) results in a detection efficiency of 94% and 89%, respectively. This is a very good sorting rate for such a complex material stream as the one in question.

Paper, wood and wood-based materials were initially not included in the liquefiable sorting process. These fractions are classified as "good" because their calorific value is significantly lower than that of pure plastic mixtures, and their chemical properties differ during liquefaction. However, since the proportion of these fractions in the total stream is relatively high, and the material can also serve as a desirable carbon source during liquefaction, it could also be classified as "good" material – either entirely or in an acceptable proportion. The Sort4Circle sorting system enables a clean separation and adjustment of the...

desired material composition. The final evaluation can therefore be made by weighing the technical and economic parameters of the overall process.

4.1.8 Further development of measurement technology – MIR reflection spectroscopy

Black plastics constitute a significant proportion of many waste streams – particularly engineering plastics (e.g., from the automotive sector), but – as the sorting trials in this project have shown – also commercial waste. Therefore, it is desirable to enable the sorting of black objects into as many polymer fractions as possible. The NIR reflection spectroscopy measurement method cannot achieve this for physical reasons, since the black pigment is usually carbon black, and carbon black exhibits broadband absorption in the NIR range, meaning the reflected intensity is insufficient for detection.

This limitation can be circumvented by shifting the measurement to the mid-infrared range (2 μm – 5 μm wavelength). In this range, the absorption of the carbon black pigment is no longer problematic, and spectral bands exist that can be used to differentiate between some types of plastic.

A particular challenge when applying this measurement technique in sorting is the measurement speed. At a belt speed of 1 m/s and an assumed minimum part size of 50 mm, the exposure time is only 50 ms. This is too short for many (FTIR¹) spectrometers to obtain a sufficient signal. Polysecure therefore uses a

¹ Fourier transform infrared

The spectrometer uses a special photon upconversion technique. Before measurement, the light was converted from the MIR spectral range to the visible range, making it detectable with a conventional, fast, and sensitive silicon chip.

The illumination is provided by a ceramic heat emitter whose spectral emission curve is tailored to the measuring range.

This technology enables fast, robust yet relatively cost-effective detection of MIR reflection spectra and thus the use of this measurement technology in sorting technology.

For evaluation purposes, a test rig was first set up in the laboratory with a light source and spectrometer above a conveyor belt to conduct initial tests. In the next step, the measurement technology was implemented in a demonstration sorting system to demonstrate its integration with the plant technology (Figure 20).

²The system combines the results of NIR, MIR and color measurements to obtain the most accurate information possible about the material and color of an object and to be able to sort it accordingly.

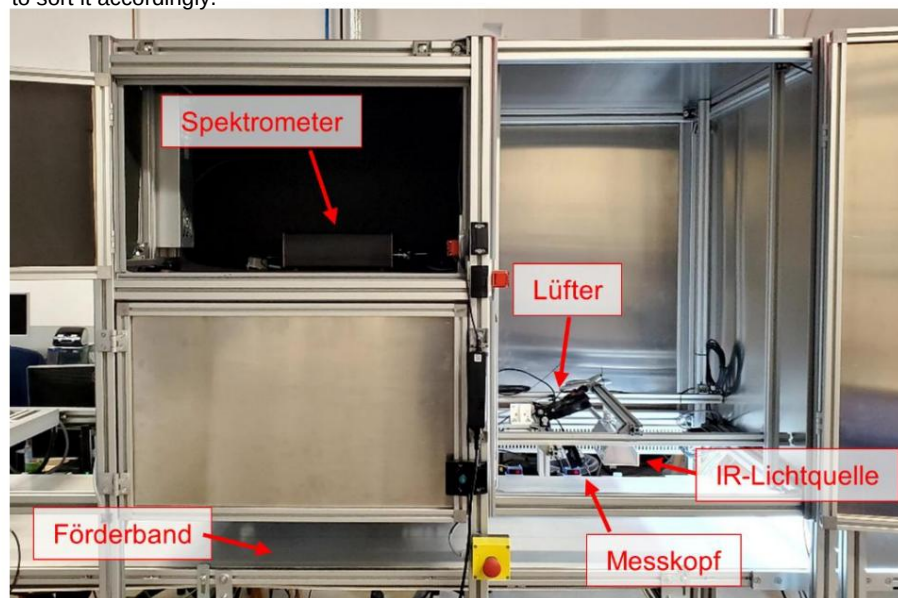


Figure 20: MIR detection chamber in demo sorting plant

Figure 21 shows measured spectra (after preprocessing by smoothing and derivation) of black samples made from the polymers PE, PP, and PA. The data clearly show distinct features in the wavelength range of 3 μm to 3.5 μm , which are suitable for differentiation. (The feature that always occurs at approximately 4.3 μm is due to the absorption of CO₂ in the air in the beam path.)

The similarity matrix in Figure 22 shows the deviation between any two different spectra based on the gray value. The darker the shade, the greater the deviation and the more reliable the differentiation from other polymers. For PA, PP, and PE, there are clear spectral differences that allow for reliable differentiation.

For other combinations, e.g. between PC, PEEK, PK and POM, the distinguishability is not yet sufficient.

Polysecure is continuously working on further improving the quality of the measurement data and optimizing the evaluation algorithm.

² The plant itself and its development were not part of the RohWerKBaWü project.

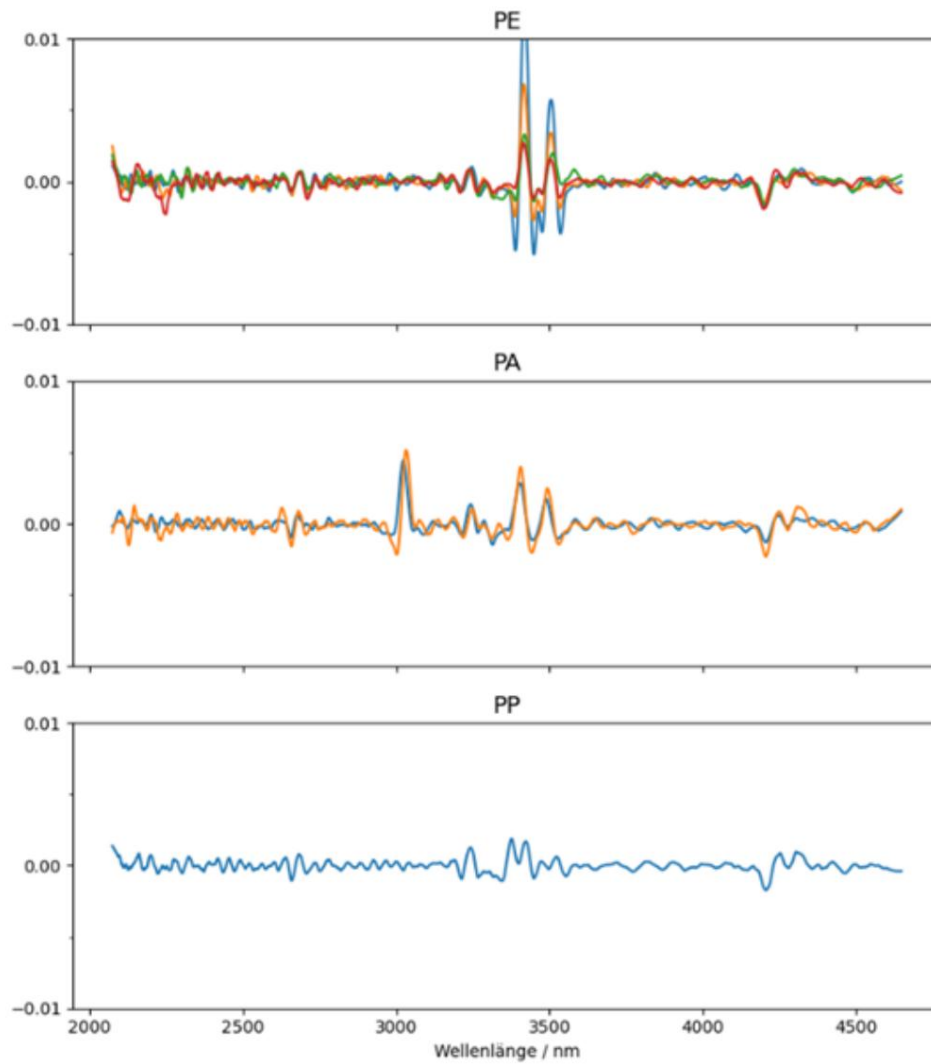


Figure 21: Target spectra (after preprocessing) for the three most important and easily distinguishable polymers PE, PA and PP

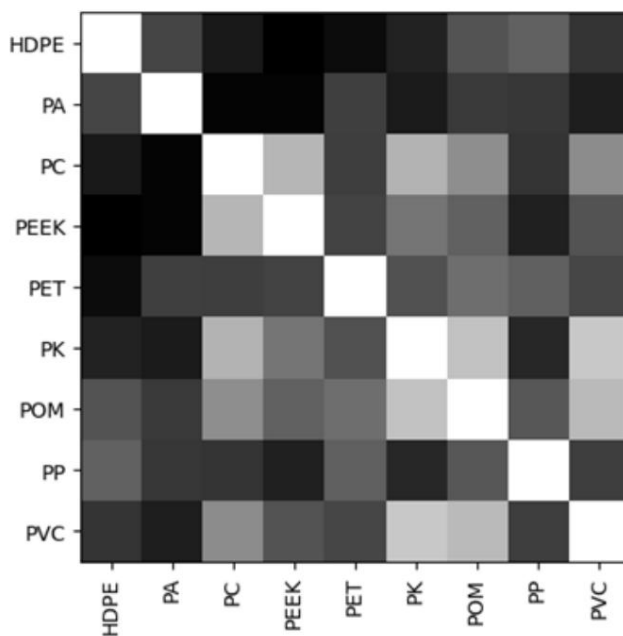


Figure 22: Similarity matrix of measured spectra for 9 different polymer types. The darker the gray tone, the higher the deviation and the better the distinguishability.

4.1.9 Sort4Circle calorific value analysis

The good fractions obtained from the Sort4Circle sorting process (see Table 4) from F1.2 and F2.2 were sent to CARBOWEST in Ennigerloh. As shown in Figure 23, the 3D parts were unsuitable for sampling and further processing in the laboratory (too large) and had to be crushed beforehand. For this purpose, the individual samples were manually re-sorted (building materials) and pre-crushed in a small hammer mill (Figure 24) for laboratory use.



Figure 23: Sample presentation and manual sorting



illustration 24: Cutting mill for
Sample crushing in Ennigerloh



Figure 25: Crushed samples for laboratory analysis

The result of the pre-crushing is shown in Figure 25. All solid particles were successfully homogenized. In the ECOWEST laboratory, the samples were analyzed for calorific value, ash content, density, and moisture content. The analysis results are presented in Table 8.

Table 8: Laboratory results of samples extracted by Sort4Circle

		Dense humidity	Snow	Calorific	Ash	Mass proportion	
			d-ability	value	content		
CW2508Polysecurer	F1.2_1	521	0.65	good	29	0.54	60
CW2508Polysecurer	F1.2_2	271.16	0.87	good	39.4	5.81	130
CW2508Polysecurer	F1.2_3	626.21	0.39	average	42.2	4.1	140
CW2508Polysecurer	F1.2_4	21.75	0.149	good	27.3	13, 19, 20	4.5%
CW2508Polysecurer	F1.2_5	568.47	1.32	good	37.7	0.99	95
CW2508Polysecurer	F2.2_1	466.95	0.65	medium	36.3	3.75	71
CW2508Polysecurer	F2.2_2	626.3	0.27	good	39.5	1.46	290
		kg/m ³			MJ/KG	Weight-%	G

With the exception of sample F1.2_4, which frayed during comminution and has a measurably high inert content, all other samples are very well suited for mechanical and/or chemical processing. In particular, the fractions with almost 40 MJ/kg should be subject to at least chemical recycling or even mechanical recycling.

However, the quantities that can be sorted by hand in the S4C test facility are too small for mechanical recycling, so a real marketing/customer test could not be carried out – for this,

- a) the Sort4Circle system will be equipped with an automatic singulation line adapted to the EBS/commercial waste stream and a storage unit
- b) larger sample volumes of the EBS stream (ton scale) are either drawn from the Korn plant and sorted at Polysecure, or the S4C sorting line at the KORN site is connected to the sorting plant.

Regarding processing in chemical recycling, an unqualified recommendation can be given. In terms of quality, it is even comparable to PO85 or PO95 (Table 9), which is available on the market and is also used for mechanical recycling.

Table 9: Comparison of the generated S4C qualities with existing PO95 and PO85 qualities Qualities on the market

	Unit Specification	CARBOWEST	PO-85	PO95	F2.2. S4C	F1.2 S4C
Date			Jul 25	Jul 24	Jul 25	Jul 25
Calorific value Ho MJ/kg	>24 Moisture		36.85	40.1	38.9	38
content %v.OS	<10 %v.OS <10 Ash		0.97	0.80	0.34	0.75
			5.58	4.50	1.91	3.86
chlorine	%v.OS <0.4		0.30	0.15	nb	nb

4.2 Strand B: TBSlight

4.2.1 Experimental objective

The aim of the project activities defined in strand B was to demonstrate the feasibility of a closed-loop system for a plastic packaging fraction, using LDPE/PA multilayer film packaging as an example. Since these composite films cannot be separated by type using conventional sorting methods, marking with fluorescent markers was to be used as a sorting criterion. The closed-loop process to be demonstrated for this stream consists of the following process steps:

1. Production of marked PA/PE multilayer films
2. Production of test packaging from the film material
3. Mixing of the marked packaging into a background stream of unmarked film packaging waste
4. Sorting in a NIR sorting system equipped with a so-called TBSlight add-on at KORN according to the fluorescence signal of the markers
5. In-process or raw material recycling of the sorted film material into new plastic
6. Production of new films and finally packaging with re-marking

At least steps 1 to 4 of this process should be carried out in the project to demonstrate feasibility on an industrial scale and to derive key performance indicators.

4.2.2 Planned experimental procedure

To implement the TBSlight process, the required marker concentration must first be determined. Since the sorter models installed in recycling plants differ in their measurement technology and, in particular, their sensitivity, it must be ensured that the marker concentration is sufficient for the sorter being used. On the other hand, the concentration should be set as low as possible to minimize the process's operating costs.

The marking can, in principle, be done either by mixing the marker into the plastic during the production of the films or by printing it on the packaging.

Marker-containing printing ink. For this test, marking in the solid material was chosen in consultation between the manufacturer Südpack and Polysecure, as the simulated material flow of PA/PE multilayer films is often unprinted and this therefore represents the more realistic application. In this procedure, the planned sorting test consists of the steps shown in Figure 26.

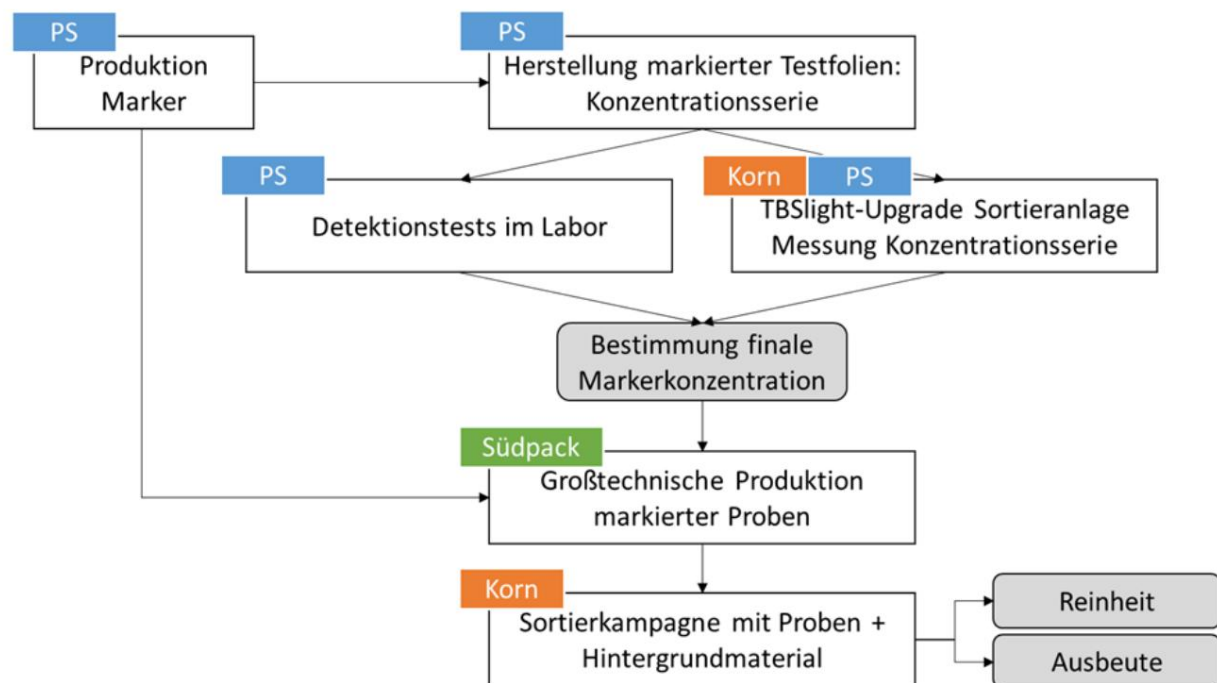


Figure 26: Flowchart of the TBSlight sorting test

4.2.3 Production of labeled test foils

For the pre-characterization of the NIR sorter, Polysecure produced two sets of test films with a series of concentrations. The marker concentrations used were 10, 20, 50, 100, 200, 500, 1000, 2000, and 5000 ppm. This wide range covers the entire practically usable concentration range approximately logarithmically, ensuring that, despite the sorter's still unknown sensitivity, at least one concentration will produce a measurable signal in the correct magnitude range. One series was produced in natural PP and a second in white PP to allow the manufacturer greater flexibility in film production, enabling them, for example, to utilize an existing production line in either natural or white. The specific polymer itself is not critical, as long as the natural color is similar. PP was chosen for production-related reasons.



Figure 27: Test slides for setting up the NIR sorter and determining the Marker concentration for the experimental campaign

4.2.4 TBSlight upgrade of the KORN sorting system

Polysecure and KORN jointly identified the best sorter in the KORN sorting plant for the trial and planned the TBSlight upgrade.

The sorter on the so-called bypass line was selected. This is a Unisort P2000 system from RTT/Steinert, manufactured in 2010. The measurement technology consists of a series of optics arranged side by side, each collecting the light from a short strip on the conveyor belt. This light was focused onto a spectrometer via fiber optic cables and an optical multiplexer (rotating mirror). NIR sorting systems of this type are no longer manufactured by RTT, now Steinert. No information was available regarding the sensitivity of this measurement technology compared to known sorters based on hyperspectral cameras, so the required marker concentration could not be estimated and had to be determined through testing in any case.



Figure 28: Sorter intended for the TBSlight trial in the KORN sorting plant

On the hardware side, several infrared lasers with line optics must be integrated to generate a laser line in the line of sight of the sorter's NIR camera. The sorter's geometry allows the laser optics to be positioned between the halogen lamps used for NIR excitation, ensuring the laser line is generated in the correct location. The necessary mounting points can also be provided. However, laser optics with a wider beam angle had to be procured to cover the entire conveyor belt within the limited available installation height. For the given belt width of 2050 mm, three of the existing 100W lasers are required. To ensure laser safety...

KORN designed a housing around the sorter. In addition, a technical and organizational laser safety concept was developed for the test period.

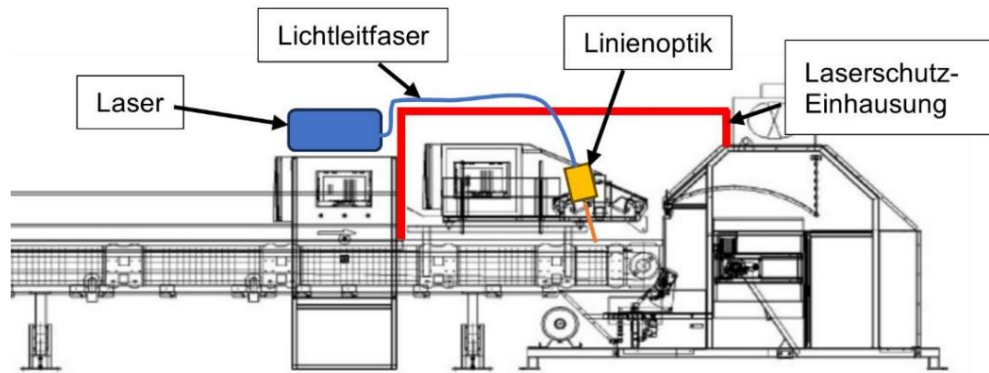


Figure 29: Schematic drawing of the NIR sorter with additional components to be installed for the TBSlight add-on. Three lasers with fiber optics and line optics were required.

On the software side, a new signal waveform, consisting of the NIR spectrum of the PE/PA film and the additional peak of the fluorescent marker, had to be measured and stored in the system control so that marked and unmarked films could be distinguished. The decision tree also needed to be adjusted if necessary. These changes could only be made by the sorter manufacturer. Therefore, contact was made with Steinert, the company that provides support and maintenance for the sorter.

Unfortunately, Steinert was unable to implement the desired modification to sorters of this type, so it was not possible to carry out the sorting trial at KORN.

As an alternative, Steinert facilitated contact with the company Umweltdienste Kedenburg, based in Beckum. They were certainly interested in conducting the trial, but finding a suitable time slot within their operational schedule proved extremely difficult. Ideally, the trial would have had to take place under extreme time pressure on a Saturday (for preparation) and for half an hour the following Monday for the actual test run. Since trials of this scale typically take longer, this was a very risky scenario. Kedenburg would have preferred to sort PP. Sorting PA/PE multilayer might not be possible there, as the trial could not be run separately from the plant's operation. One of the output fractions would always be fed into the running plant and could not be analyzed. Furthermore, additional hardware costs in the region of €10,000 would have been expected, as two sorters might have been required for a complete two-stage sorting process, necessitating additional lasers. Given these circumstances, this alternative had to be abandoned.

In general, the main purpose of the sorting trial was to identify TBSlight at KORN Recycling.

The aim was to demonstrate the results in order to incorporate them into the technical and economic analysis of the specific case. An experiment with a different sorter, using different technology and test material, would have yielded little to no data or insights that had not already been obtained in previous Polysecure trials. For this reason, the TBSlight experiment was ultimately abandoned in this project.

Instead, it was decided that KORN would conduct additional trials and analyses on a modern NIR sorter from TOMRA at the plant. Due to its design, this sorter is not suitable for TBSlight. However, it is more modern and offers better parameter adjustments than the other sorters at KORN, and is therefore well-suited for investigating and optimizing conventional sorting based on NIR technology. These trials are described in section 4.3.

4.3 Line C: Optimization TOMRA and post-crushing 3

4.4 Problem description

The material recovery of plastics from commercial and bulky waste presents a significant challenge for the circular economy. The heterogeneity of these material streams, their varying composition, and the high proportion of contaminants necessitate a targeted combination of mechanical pretreatment and sensor-based sorting to provide high-quality EBS++ as a basis for chemical or mechanical recycling.

As part of this study, the rolling material flow of a processing plant was first analyzed in detail. The focus was particularly on the 3D fractions (solid materials such as plastic parts). The aim was to systematically evaluate the separation efficiency between recyclable plastics and interfering substances.

The original plan was to conduct trials with labeled plastic materials on the sorting system. This was intended to enable the traceability of individual polymer types in the sorting process and to quantify the detection accuracy. However, implementing this approach proved impossible because the necessary adaptation of the existing NIR systems and the corresponding parameterization were not feasible.

To utilize existing resources efficiently and effectively, the focus of the work was placed on investigating sheet-like materials. Systematic tests were conducted using a TOMRA NIR sorter to obtain a comprehensive picture of the sortability of PE film, rigid PE, PP, and PMMA from commercial and bulky waste streams.

The findings are intended to demonstrate how varying selected process parameters at the ballistic separator and the NIR sorter can optimize the purity and yield of the target polymers while simultaneously minimizing the proportions of PVC (chlorine) and inert materials. This work thus provides practical approaches for optimizing plant operation and increasing the quality of the feedstock for the chemical recycling of RDF (refuse-derived fuel).

4.5 Problem description

Commercial waste streams are characterized by high material heterogeneity, a fluctuating input mix, and an above-average proportion of contaminants. In addition to classic packaging plastics such as polyethylene (PE) and polypropylene (PP), this waste stream also contains engineering plastics such as polymethyl methacrylate (PMMA), as well as significant quantities of chlorine-containing materials (PVC) and mineral inerts.

The aim of this work is to separate the plastics PE film, rigid PE, PP, and PMMA with the highest possible purity from the flat sorting stream of a mechanical processing plant. These fractions are particularly relevant for chemical recycling.

This results in two essential quality requirements for the target products:

1. Minimizing the chlorine content (PVC):

Even small amounts of PVC contamination have a serious negative impact during further processing in chemical reactors, as they impair material properties and can lead to the formation of HCl and dioxins during thermal recycling [4]. The chlorine content should be well below 1%. Therefore, it is necessary to keep PVC out of the target streams as much as possible.

2. Reduction of inert material content (ash content):

³ Since the installation problems and the workaround were only worked out during the balance run, the ones in strand C were unavailable. Solutions developed by KORN will only be available after the CARBOWEST balance sheet run.

Inert materials such as glass, stones, and mineral residues, as well as individual components of plastics, pose a significant problem in chemical recycling plants. They cause disruptions in the production process, require costly filtering, can lead to increased wear and tear on the equipment, and must be disposed of as waste at considerable expense. Furthermore, no oil can be extracted from this portion of the input material, thus reducing the yield. The goal is therefore to minimize the proportion of inert materials.

The difficulty lies in the fact that, in practice, both PVC and inert materials exhibit similar size and shape characteristics to the target polymers. This makes them difficult to separate using conventional mechanical separation methods. Furthermore, flat 2D materials (films, sheets, composites) represent a particularly challenging sorting group: overlaps, adhesion (due to moisture), and moisture itself lead to a degradation of the NIR signals and increase the rejection rate.

Against this background, the combination of mechanical pre-separation (ballistic separator) with sensor-based post-sorting (TOMRA-NIR sorter) is a proven approach to separating the target plastics from contaminants. However, the effectiveness of this sorting chain depends heavily on the operating parameters. Therefore, a series of experiments was conducted in this work, specifically varying the following parameters:

- Ballistic separator: tilt angle and impact frequency
- TOMRA NIR sorter: Belt speed, nozzle pressure and confidence level

By selectively varying these factors, the aim is to investigate how the sorting quality can be changed with regard to purity, yield, and PVC and inert material content. The goal is to derive recommendations for practical operation and to enable optimized, purity-oriented operation of the plant.

4.6 Plant description (area sorting stream)

4.6.1 Overview The

plant combines mechanical pre-separation (ballistic separator) with sensor-based sorting (NIR) and downstream secondary shredding as well as metallic separation.

4.6.2 Ballistic separator (manufacturer: Stadler)

The ballistic separator separates the input stream into a flat **2D fraction**, a solid **3D fraction**, and a fine fraction based on shape, weight, and movement. This is achieved using oscillating screen plates whose tilt angle and impact frequency are variably adjustable. Flat materials (films, paper) are transported upwards, while 3D solids are discharged downwards, and fine particles are separated through the screen openings. The tilt angle and impact frequency are adjustable for the 2D fraction.

Key parameters for stabilizing the film fraction and reducing foreign matter.

4.6.3 TOMRA NIR sorter (first stage)

The 2D fraction was classified on a TOMRA-NIR sorter. This NIR sorter uses near-infrared spectroscopy in the SWIR (short-wave infrared) range. Materials on the conveyor belt are optically detected, classified based on their specific spectral signature, and selectively discharged via a compressed air nozzle bar. Besides material detection, **belt speed, nozzle pressure, and confidence level** are crucial for sorting accuracy. In the first stage, primarily PE film was discharged, while non-PO (e.g., wood, paper, PET, PVC) remained in the residue. Key parameters: belt speed, nozzle pressure, and confidence level.



Figure 10: TOMRA-NIR sorter used

4.6.4 Second NIR sorter (polishing stage)

To increase product purity, a polishing stage follows in binary mode (PVC or non-PVC) with stricter settings (higher confidence, shorter nozzle pressure time) to minimize residual rejects (including PVC risks).

4.6.5 Re-crushing (Lindner Comet)

The subsequent shredding is carried out as standard using several Lindner Comets. The defined particle reduction process homogenizes particle shape and bulk density and reduces adhesion. The Komet post-compression unit is an integral part of the line; temporary, trial-related alternative units are used exclusively in the trial phase. described.

4.6.6 Iron/FE Deposition

After the comet stage, FE deposition is carried out using a magnet to remove ferromagnetic contaminants and further ensure the product quality of the EBS fractions.

4.6.7 Schematic material flow



Figure 11 Process chain of the 2D fraction (series production)

4.7 Test procedure on the ballistic separator

4.7.1 Objective

The ballistic separator forms the first separation stage for the two-dimensional (2D) fraction. The aim of the test series was to investigate the influence of selected operating parameters on the purity and yield of the 2D fraction. The primary focus was on how the separation sharpness between films/plastics on the one hand and unwanted 3D fractions such as wood on the other could be optimized. Figure 12 shows the preparation and execution of the sample loading using a telescopic crane.

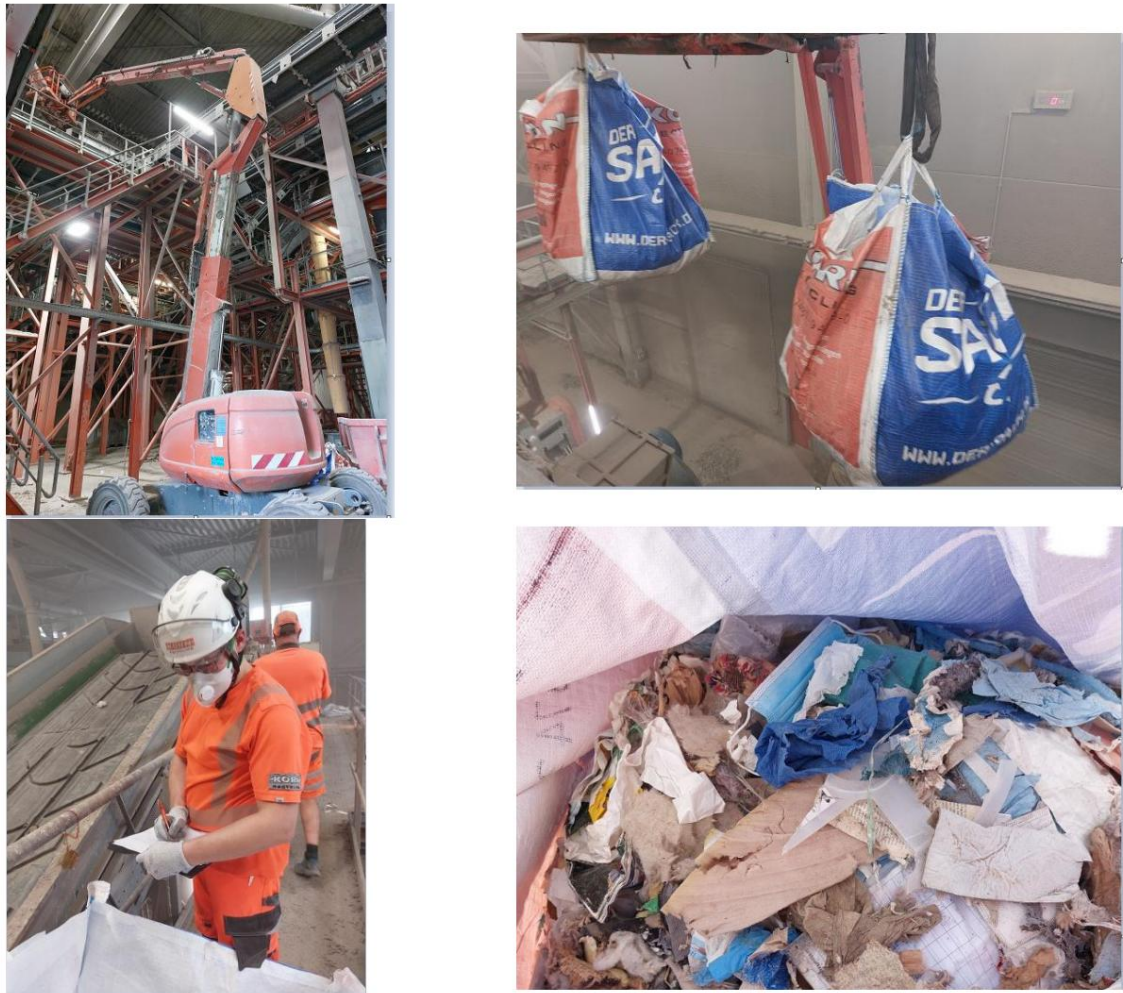


Figure 12: Preparation for the task of handling the samples

4.7.2 Investigated setting parameters

For the investigations, two key settings of the ballistic separator were systematically varied:

- Inclination angle of the sieve plates:
Steeper settings favor the separation of heavier and thicker-walled materials into the 3D fraction, while shallower angles allow for a higher output of films in the 2D stream.
- Stroke rate (rpm):
Higher frequencies promote the rapid removal of solid materials, thereby increasing the purity of the 2D stream. Lower frequencies cause materials to remain on the machine longer, increasing the risk of mis-assignment. The speed could only be achieved through the settings on the frequency converter and had to be adjusted manually.

The variations were performed in defined steps, allowing two different angle and frequency ranges to be combined. This resulted in the creation of an experimental matrix that allowed conclusions to be drawn about main effects and interactions between the parameters.

4.7.3 Experimental setup and sampling

- Input: heterogeneous commercial waste with a high proportion of film, typical moisture content 8–12%.
- Task: uniform material dosing via feed belts, carpet height <150 mm.

- The material flow was controlled via the TOMRA-NIR sorter and the respective composition of the fractions was measured over time in % proportions.
- Evaluation criteria: Proportion of wood fraction to surface material
- In addition, the proportion of flat material was compared to the quantity abandoned set and visually assessed.

4.8 Test procedure on the TOMRA-NIR sorter

4.8.1 Objective

Following mechanical pre-separation by the ballistic separator, the effects of the key parameter settings of the TOMRA-NIR sorter on the sorting quality of the sheet fraction were to be investigated. The focus was on the purity and recovery of the target polymers (PE film, PE, PP, PMMA) as well as the minimization of PVC and inert content.

4.8.2 Parameters examined

The following parameters were systematically varied:

- Belt speed (m/s): low speed allows for longer detection times and more precise ejections, higher speed increases throughput with a potentially higher mis-throw rate.
- Nozzle pressure (bar): lower pressure reduces carryover effects, higher pressure improves the separation of small objects, but increases the risk of over-ejection.
- Confidence Level (%): Threshold for detection reliability; higher values increase purity, lower values improve yield.

4.8.3 Experimental Procedure

The flat fraction from the ballistic separator was fed into the NIR sorter. For each experimental setup, the system ran stably for a defined duration (approx. 10–15 minutes) before samples were taken from the target stream and the residue. The samples were then classified (visual inspection) and evaluated with regard to purity, yield, and contaminant content.

To assess purity at the ballistic separator, the wood fraction was also used as a benchmark. Wood generally lacks flat properties and was

Therefore, it was predominantly transferred to the 3D fraction. Individual pieces or panels of wood that nevertheless remained in the 2D stream were considered an indicator of impurities. This procedure allows for a practical assessment of the ballistic separator's separation efficiency, since wood is common in heterogeneous commercial waste and can be reliably classified manually due to its unambiguous material properties (color, structure, density).

A low wood content in the 2D stream was therefore interpreted as a positive indication of high purity of the foil fraction.

To determine the purity of the sorted plastic fractions, a practical and rapid method was used. A 1 kg sample was taken from the target stream and manually sorted on a sorting table. The materials were then visually and haptically classified into the target polymers (PE film) and a residual material fraction (PVC, PET, paper, inert materials, wood, other). This classification was based on typical identifying characteristics such as appearance (translucent, opaque, printed) and feel (soft and rustling, stiff, waxy). In cases where a clear visual or haptic classification was not possible, a float-sink test was additionally used in a laboratory bucket. In this test, the sample was transferred to water, allowing the density differences of the polymers to be utilized: polyolefins (PE, PP) float, while denser polymers such as PVC or PET sink.

This combination of manual sorting and simple density separation made it possible to make a quick, yet scientifically sound statement about the purity of the sorted fractions.

To determine the inert material content, the ash content of the sorted samples was determined. For this purpose, representative subsamples were ashed at high temperature (approx. 550–600 °C). While the organic plastic components burned completely, mineral residues such as glass, stones, ceramics, or inorganic fillers remained as the ash fraction. The percentage of these residues relative to the original dry weight was documented as the ash content in % and served as a measure of the inert material content in the respective fraction.

4.8.4 Temporary post-shredding (mobile shredder from Arjes) in the experiment

To investigate the influence of particle size on detection and separation efficiency, a portion of the sorted material was additionally processed through an Arjes shredder. This unit was not part of the regular process but was specifically used for the experiment (**Figure 13**). The shredded material was then fed back into the TOMRA NIR sorter to measure changes in detection quality and sorting performance. A further portion was also processed in another mobile unit (a non-ferrous metal separator from Komptech).



Figure 13: Mobile Arjes VZ 950 titanium re-shredder

4.8.5 Serial re-shredding (Lindner Komet)

In regular plant operation, secondary shredding is carried out using a Lindner Komet, which homogenizes the particle size distribution and stabilizes the downstream recycling processes. The use of the Arjes in the experiment was therefore a supplementary intermediate step for the scientific investigation.

4.8.6 Evaluation criteria

- Yield (%) per polymer fraction
- PVC content (%) in the final product
- Inert material content (%) (visual/ash content)
- Influence of pre-shredding on detection and separation

4.9 Results and evaluation

4.9.1 Results of the ballistic separator tests

Varying the tilt angle and striking frequency had a significant impact on the composition of the 2D current.

- Stroke rate of 180 – 210 rpm
- Tilt angle of 30-40 degrees
- Wood content of 16.2% to 22.2%

Table 3: Influence of tilt angle and impact frequency on purity and yield of the 2D fraction

Neigungs- winkel (°)	Frequenz in Hz	Schlagfrequenz (U/min)	Reinheit	Ausbringung	Wirkung	Holz-Anteil in %
30	60	180	Qualität eher runter	nach oben	mehr PVC und Inertstoffe	22,20%
30	65	200	wenig Veränderung	nach oben		21,80%
30	70	210	kaum Veränderung	kaum Veränderung	Flacher Winkel und hohe Frequenz -> Effekte heben sich auf	21,20%
35	60	180	kaum Veränderung	wenig Veränderung		20,70%
35	65	200			war Referenzwert	19,00%
35	70	210	Qualität nach oben	Verluste		18,70%
40	60	180	Qualität nach oben	kaum Veränderung	trennt besser	17,80%
40	65	200	Qualität nach oben	Verluste	Reinheitsorientiert	17,30%
40	70	210	Qualität deutlich nach oben	hohe Verluste	super Trennschärfe	16,20%

Increasing the tilt angle (e.g., from 30° to 40°) and the impact frequency (e.g., from 180 to 210 rpm) leads to a significant increase in the separation efficiency between the 2D and 3D material groups. This is also reflected in the improved removal of the wood fraction.

Mechanistically, this can be explained by the enhanced gravimetric-ballistic selection: 3D particles experience earlier removal at steeper angles and higher accelerations, while flat 2D particles have longer contact times on the sieve plates. This results in higher purity in the 2D fraction. The inclusion of mineral components (inert materials) and wood has been reduced, while a moderate decrease in film removal is expected (loss of thin-walled, 3D-like particles in the 3D fraction).

the

The reference setting (35° at 65 Hz and 200 rpm) provides a robust operating window; the purity-oriented operating mode (40°, 210 rpm) maximizes the quality indicators, but requires accompanying throughput optimization (dosing, NIR parameters) to limit economic losses.

4.9.2 Results of the TOMRA-NIR tests

The investigated parameters belt speed, nozzle pressure and confidence level significantly influenced the separation efficiency of the NIR sorting.

- Belt speed of 2.4 – 3.0 m/s
- Pressure of 2.5-3.5 bar
- Confidence high and low

Table 4: Influence of the confidence level on purity and yield (PE film)

							Slides			TS
test	Band	Pressure	Confidence	Filter	Feed	Yield	PE Purity	Chlorine	Ash	Calorific
Test 1	2.4 3	5 high	5.9 97.80	3.0 2.2	low		76.6 0.26	19.1		34.5
Test 2	6.1 97	3.39 3.0	3.5 low	5.7 97	64 3.0		80.7 0.40	28.0		26.4
Test 3	3.5 high	5.8	97.42 2.4	3.5 low	6.0		77.7 0.81	30.8		24.8
Test 4	97.47	3.0 2.2	high 6.2	97.74	2.4		74.8 0.38	28.8		25.2
Test 5	2.2 high	6.0	97.48 2.4	2.2 low	6.2		79.0 0.27	19.8		36.0
Test 6	97.46						77.0 0.37	27.7		30.1
Test 7							81.3 0.25	17.6		29.5
Test 8							78.2 0.45	20.5		26.2

Varying the control parameters belt speed, nozzle pressure, and confidence level showed a highly significant influence on the sorting performance of the 2D fraction. Reducing the belt speed (e.g., from 3.0 to 2.4 m/s) resulted in a longer residence time in the detection window, leading to higher detection accuracy and improved separation between target polymers and contaminants. Simultaneously, at excessively low belt speeds, the risk of overlapping (monolayer >80%) increased, meaning that the net yield did not increase linearly.

The nozzle pressure primarily influenced the carryover effects: Low pressure levels (<2.5 bar) led to incomplete separation of small PVC fragments, while high pressure levels (>3.0 bar) increased the purity, but increased material losses in the target stream due to multiple hits and air turbulence.

The confidence level proved particularly relevant: with increasing values ($\geq 90\%$), a significant reduction in the PVC content to <0.01% was achieved, which directly contributed to a reduction in the chlorine content in the target polymers. However, this improvement in quality was accompanied by a moderate reduction in yield, as even borderline PE/PP particles were rejected.

The interactive effect of the factors showed that a combination of moderate belt speed, medium nozzle pressure and high confidence level represented the best compromise between purity and output.

4.9.3 Influence of pre-crushing (Arjes in the experiment)

The additional comminution resulted in a change in particle size and improved detectability by the NIR sorter.

The upstream ferrous and non-ferrous metal deposition led to a stabilization of the NIR signals, as metallic reflections were reduced. This resulted in a significantly higher purity, particularly in the positively discharged PVC stream, and thus a substantial reduction in the chlorine content of the final product.

Table 5: Results with pre-shredding (PE film)

							Slides				
test	Band	Pressure	Confidence	Feed	dry z	PE	Purity	Chlorine	Ash	Caloric	in
Test 1 broken.	2.4 3.5	high 5.8	97.12	2.4 2.2	high	81.7	0.22		18.8 34	1	
Test 2 broken.	6.1 96	94 3.0	3.5 low	5.9 97	40 2.4	85.8	0.09		16.9 34	3	
Test 3 broken.	3.5 low	5.8 97	83			76.3	0.47		27.1 29	8	
Test 4 broken.						78.4	0.33		25.2 32	5	

4.10 Overall evaluation of the test results

The combined results from ballistic separator and NIR tests show the following Trends:

- With a steeper inclination angle and increased stroke frequency, the purity of the 2D-Fraction, with slightly decreasing application.
- Low belt speed and high confidence values lead to an improvement in purity, but at the expense of output.
- The nozzle pressure showed a critical balance: values that were too low reduced the cutting sharpness, values that were too high increased the particle carryover.
- The temporary post-crushing with the Arjes improved detectability and was able to remove inert components, especially FE components.
- Overall, the PVC content and thus the chlorine content in the target streams could be reduced to below 0.3% in several variants, while maintaining high purity of PE film and PP.

5. Application of the developed sorting processes to generate the EBS++ and PA-PE composite films fraction

5.1 Preparing the feedstock selection at KORN

The production of the material EBS++ (A) at KORN, which was liquefied during the balance run at CARBOWEST, was monitored by two employees of carboliq/RECENSO (SAS/LVE) and analyzed and evaluated on site in Albstadt. Various EBS fractions were examined; these are shown in Figure 14 and Table 6.

For sample 1, produced during the night shift on February 20, 2025, the calorific value, ash content, and chlorine content were determined. Additionally, a sample (sample 2) from the day shift on February 19, 2025, a sample from storage (sample 3), and a sample (sample 4) from a discharge point in the plant (F2.4) were taken and analyzed. Based on the results, it was decided to use four wheel loader buckets of sample 1 and four buckets of sample 4, totaling approximately 16.5 tons. Furthermore, eight big bags (approximately 1.5 tons) of EBS++ (B) were loaded onto the truck as F2.4A and prepared for transport. In total, 18.14 tons were shipped (see also).

Figure 15)



Figure 14 EBS storage facility at KORN with wheel loader for loading the truck (HN-FK-450)

Table 6: Analyses of various EBS samples at KORN

		Spec	Sample 1	Sample 1	Sample 1	Sample 2	Sample 3	Sample 4
			production			Daily productivity		
			Night			on	Storage	F2.4A
			20.02.25			February 19, 2025		
		CW2502KO45	250220	830	SAS	CW2502KO45	250220	830
Measurement at			GRAIN	GRAIN	CWEST	GRAIN	GRAIN	GRAIN
Calorific value MJ/kg	24		26.26	24.89		28.21	20.32	22.30
Ash content %	<10		12.50%	7.50%	7.11%	2.70%	11.50%	6.90%
chlorine	%	<0.4	0.54	0.34		0.32		0.2



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CARBOWEST GmbH

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Zielort Nr. 98776

Beförderer: FK Spedition GmbH

Wiege-/Lieferschein Nr.

2209061 /A /2383448

KFZ-Kennz.: HN-FK 450

Einzelwiegung: 20.02.25 12:49

Bezeichnung: 1354 Brennbare Abfälle 25mm Kat.1(Brennstoffe aus ... 19 12 10 18,140 to

Brutto: W 10009802
34.720 kg

Tara: W 10009759
16.580 kg

Netto:
18.140 kg

Unterschrift Wiegemeister

Unterschrift Anlieferer/Fahrer

Beleg erstellt am 20.02.25 Waage Korn Recycling GmbH,
Messwerte aus frei programmierbarer Zusatzeinrichtung. Die geeichten Messwerte können eingesehen werden.
Wir weisen darauf hin, dass der Fahrer des Fahrzeuges für Gewichtüberschreitungen selbst verantwortlich ist.

Figure 15 Cradle and delivery note of the KORN campaign (EBS++ (A+B))

6 drivers of the EBS++ faction from KORN at CARBOWEST

6.1 The aim of the experiment

KORN Recycling GmbH is interested in proof of the technical capability of the CARBOWEST liquefaction plant in Ennigerloh and the general reliability of the patented carboliq technology when using its alternative fuel from the plant in Albstadt.

The EBS++ (A+B) produced in Chapter 5 was processed in two campaigns with a total duration of 20 days during a single, balanced run. Scheduled sampling was carried out. The results are documented in reports.

Other secondary objectives of the test are

- Trouble-free and uninterrupted operation of the system
- Reaching a steady state
- Achieving consistent product quality
- Marketability of the produced petroleum substitute
- Logging and presentation of the entire trip
- Integral mass, energy and material balances

6.2 Feedstock selection and delivery / shredding at GRE

The following documents the delivery of the KORN EBS material, which was liquefied as part of the agreed balance run.

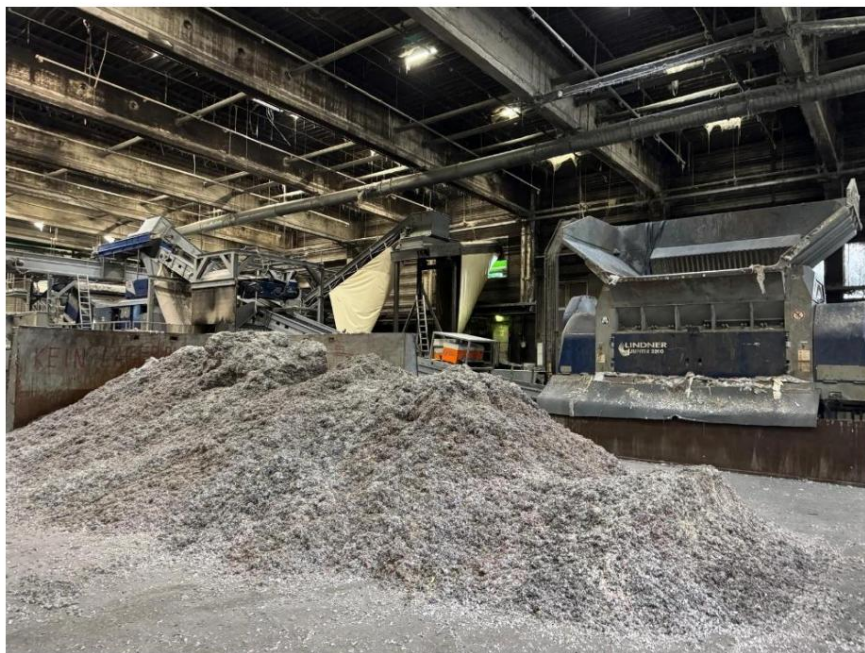


Figure 16 Delivery of the KORN EBS++ material to GRE on Friday, February 21, 2025, at 8:30 a.m.



Figure 17 KORN EBS++ material after contract shredding (see Densification)

Due to CARBOWEST's requirement regarding particle size, the material was further shredded to 30 mm at a contract shredding facility. This ensured, among other things, that any clumps that had formed during storage were removed.

Figure 16 shows the material after delivery to the contract shredder, and Figure 17 shows the material after shredding at CARBOWEST.

6.3 Pre-characterization of the feed material in the laboratory

6.3.1 Basic Characterization

The delivered material was sampled and taken to the ECOWEST laboratory for pre-characterization, where it was pre-analyzed according to the CARBOWEST standard analysis (see sequence). Figure 9).

Table 7 shows the material properties of KORN EBS material compared to typical carboliq feedstock. The calorific value is low at 25 to 28 MJ/kg and at the lower end of the limit values. The ash content is rather high at 3 to 7%, which is due to the higher inert content. The cutting properties are good. Overall, the (material)

The material quality is as expected for a waste-to-energy plant. Further analyses and sampling during the test run will show whether the material quality can be considered homogeneous and constant over longer periods.

Table 7 Comparison of the samples of KORN EBS++ material with the values of the typical Feedstocks

				
Material property unit		Typical Feedstocks	KORN Albstadt Sampling	KORN Sample Ennigerloh
Ash content	% (m/m)	< 5	Approximately 7	7.11
Calorific value	MJ/kg	25 to 41	26.1	25.20
bulk density	kg/m ³	50 to 100	-	-
Humidity	% (m/m)	5	-	4.65
Cutting ability		good	good	good

6.4 Balance sheet of the plant

The cycle was started on February 24, 2025, at 11:30 PM, the reactor temperature was set, and the feeding of the KORN EBS++ material began. At noon on February 24, 2025, Jürgen Lehmann was present and supervised the inventory (recording all fill levels/weights) and the emptying (zeroing) of the containers and IBCs. Since the switchover from campaign AR44 to campaign KO45 was seamless, i.e., without shutting down and restarting the plant, it takes approximately three days for the reactor to reach a steady state.

On February 25, 2025, a large project meeting took place, where all project participants were present and, in small groups, conducted a tour of the grounds of the waste disposal center to gain an impression of the EBS plant and the handling of real waste on an industrial scale.

The samples of the input material KORN EBS++ F2 and of the CLR product P1 were taken during the presence of Mr. Jürgen Lehmann (see below).

Table 8). In addition to the sample taken for standard analysis, a further sample for KORN was taken for in-house evaluation.

A morning round was conducted every morning at 8:00 a.m., during which the KORN – Employees were present and in which incidents from the night as well as the pending items for the day shift (deliveries, repairs/maintenance, other) were discussed and clarified.

Because the heterogeneity and higher levels of contamination of the input material led to various problems during operation, such as conveying issues, the driving strategy was regularly adjusted.

On March 12th, all the material from sample 2 of KORN had been liquefied. On March 14th, KO46 started with the material from sample 4 (Table 7). During this campaign, a neutralizer was added to reduce the chlorine content in the material.

The balance voyage(s) (stationary state) was unanimously declared completed on March 16th, as agreed between the parties.

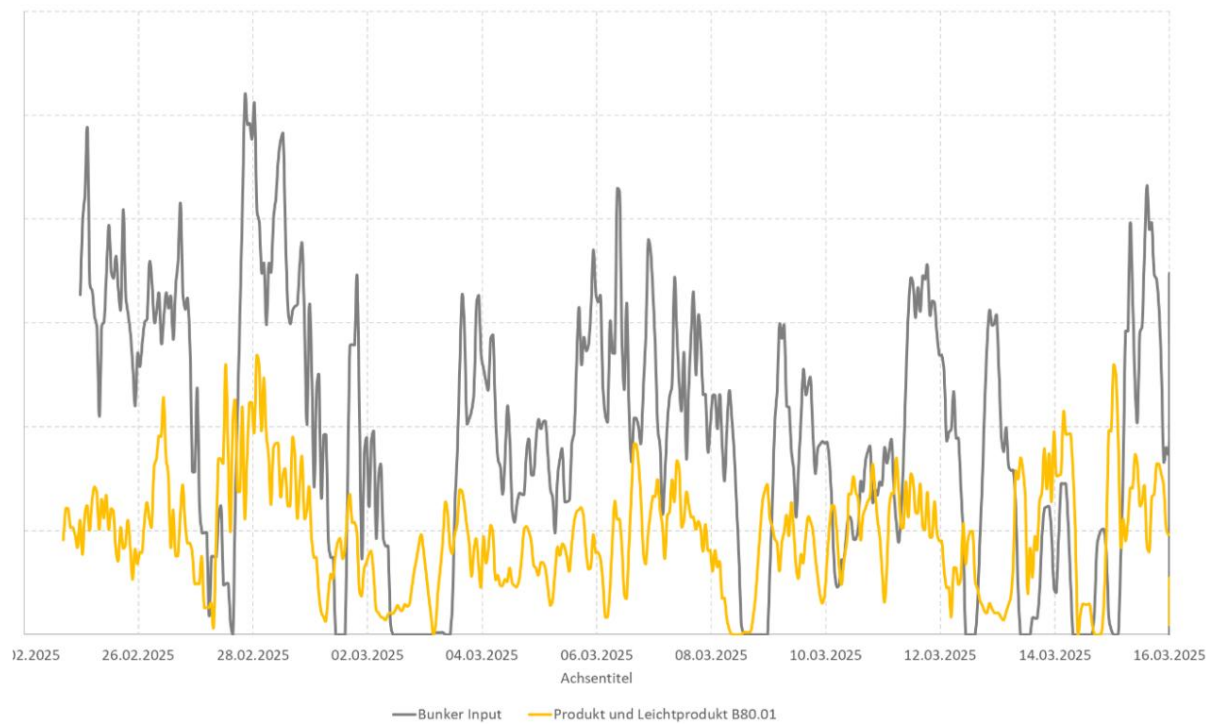


Figure 18 shows the hourly quantities produced (without absolute unit)

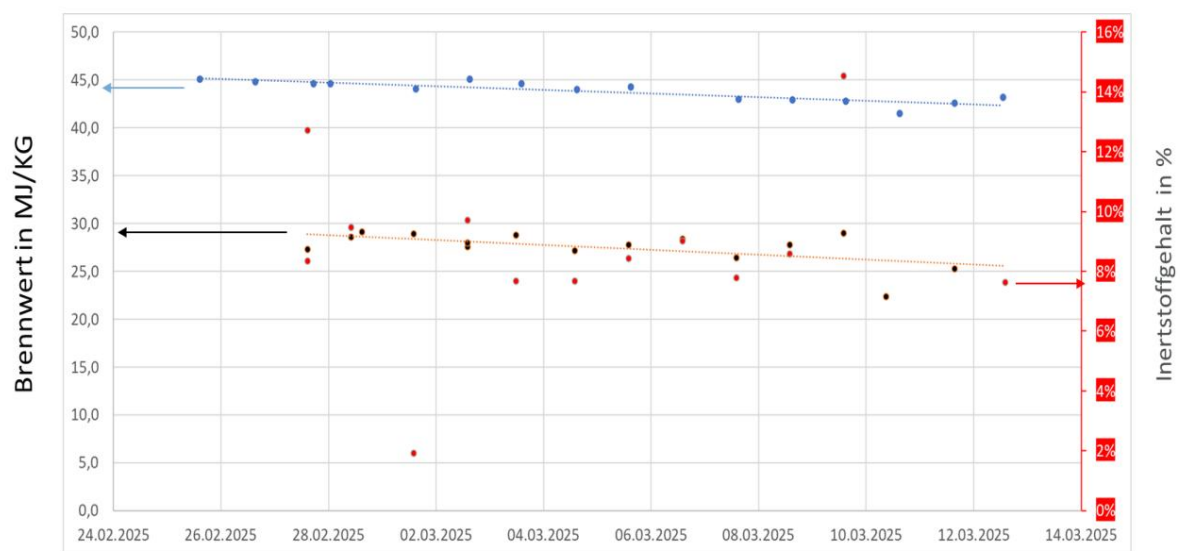


Figure 19 Time periods and calorific values of the input material and the CLR product (left axis, right axis: inert material content)

Figure 19 shows the entire period of the balance run (24.02.2025 to 14.03.2025).

The calorific values are high and decrease slightly towards the end of the campaign – since the entire production of KO45/KO46 was delivered as part of a tank truck, the product quality meets petrochemical specifications. Thus, the usability of EBS++ in the petrochemical industry has been demonstrated. The slight reduction in calorific value is negligible.

6.5 Analyses and measurement results

Table 8 Calorific value, bulk density, ash and water content of the F2 feedstock during the balance run

	Cutting capacity t	bulk density	Water content t	Calorific value	Ash content
abbreviation		rSchuett.F1	wFeucht.F1	DCHF1	wAsh.F1
Date / Unit		kg/m ³	weight%	MJ/kg	weight%
February 21, 2025 11:00		-	4.65	25.2	7.11
Good February 27, 2025		-	3.6	27.3	8
14:35 Good February 28,		-	3.7	28.6	13
2025 10:10 Good March 1,		-	2.73	28.9	9
2025 14:01 Good March 2,		110.47	4.22	28.0	8
2025 14:01 Good March 4,		89.73	2.8	27.2	8
2025 14:00 Good March 5,		107.1	3.15	27.8	9
2025 14:00 Good March 6,		106.92	2.7	28.4	7
2025 14:00 Good March 7,		90.69	3.29	26.4	10
2025 14:00 Good March 8,		104.56	2.12	27.8	8
2025 14:00 Good March 9, 2025 14:00 Good		96.97	3.75	29.0	9
March 10, 2025, 9:00 AM	Good	109.94	7.65	22.4	15
March 11, 2025, 3:30 PM:	Good;	97.37	6.96	25.3	11
March 12, 2025, 2:00 PM:	Good	81.58	3.14	20.7	21
mean	Good	99.5	3.9	26.6	10.2

Table 8 shows the measurements of calorific value, bulk density, moisture, and ash content taken during the balance sheet analysis. It is clearly evident that the feedstock is relatively uniform. The calorific value can be assumed to be very stable over time. The ash content shows that the material contains an increased proportion of inert components, i.e., components that cannot be liquefied.

6.5.1 Testing methods

Table 9 Test parameters and test methods of the company ASG

Test parameters	Test method
Carbon content	ASTM D5291, method D :2021
Hydrogen content	
nitrogen content	
oxygen content	
Sulfur content	
Chlorine content	ASTM D5622 :2017
Fluorine content	DIN EN 15408 :2011
Bromine content	

Iodine content	
metals	DIN EN ISO 11885 :2009
Mercury (Hg)	ASTM D7623 :2020
Acid number	DIN EN 12634 :1999
Flash point	DIN EN ISO 3679 :2023
Pourpoint	DIN EN ISO 3016 :2017
Density (15 °C)	DIN EN ISO 12185 :1997
Water content	DIN EN ISO 12937 :2002
Distillation process (GC- Procedure)	ASTM D7169 :2020

Table 9 shows the test parameters and test methods of ASG. These are internally monitored and regularly audited. They represent the usual standard measurements and -

The procedure is suitable for the respective measured quantity. As already described, it has been established that the accuracy of ASTM D5291, method D:2021 is insufficient for the nitrogen content requirement of <5,000 ppm.

7. Evaluation of results, creation of investment plan (GRAIN)

7.1 Introduction and General Information

7.1.1 Problem Statement and Motivation

Global plastics production has been growing steadily for decades, exceeding 350 million tons in 2020. Forecasts predict this amount will almost triple by 2050. This growth is leading to an increasing burden of plastic waste, which cannot be adequately managed using traditional mechanical recycling methods. Mixed or contaminated plastic fractions, in particular, are still predominantly used for energy recovery (incineration), resulting in the loss of valuable raw materials and significant CO₂ emissions.

7.1.2 Objective of the analysis

The aim of this analysis, based on the campaign results, is to develop a viable business model for the chemical recycling of refuse-derived fuel (RDF) from mechanical waste processing (RDF++) using the patented carboliq technology. The report will demonstrate how integrating this technology into existing waste processing operations can generate not only environmental but also economic benefits. To this end, the market and environmental conditions will be analyzed, the company strategy described, the technological process chain explained, and a business model canvas and a financial model developed over a ten-year period.

Furthermore, the feasibility of the business model for venture capital was examined.

7.1.3 Methodological approach

The methodological approach is based on a combination of literature and market analyses, the evaluation of existing pilot projects, and business modeling. A Business Model Canvas was developed that presents the essential building blocks of the business model in a structured manner. In addition, a financial model was created that, based on assumptions regarding investment and operating costs, market prices, and regulatory frameworks, enables a cash flow analysis over ten years. The analysis was rounded out by a venture capital readiness assessment and a risk and mitigation analysis.

7.2 Market and environmental analysis

7.2.1 Macro trends and regulatory framework

Global plastics production continues to increase sharply. Forecasts predict that annual production could exceed one billion tons by 2050. This growth exacerbates the problem of waste management, particularly since global recycling rates are currently inadequate. In Europe, the European Union is setting increasingly stringent targets: at least 30% recycled content in plastic products is to be used by 2030, and the EU aims for a fully circular economy by 2050. Instruments such as carbon pricing within the framework of the European Emissions Trading System and government funding programs to support new recycling technologies are also key drivers. This has made the thermal utilization of alternative fuels, for example by the cement industry, more difficult.

7.2.2 Limitations of mechanical recycling

Mechanical recycling is currently the most widespread technology, but it reaches its limits with more complex waste streams. While single-type plastics can be recycled, the process often results in a loss of quality.

Particularly with multi-layer packaging, composite materials, or heavily contaminated plastics, material recycling is hardly possible. These fractions are predominantly used for energy recovery as refuse-derived fuel, resulting in the loss of valuable raw materials and greenhouse gas emissions.

7.2.3 Potential and growth prospects of chemical recycling

Chemical recycling addresses precisely the gap left by mechanical recycling. Processes such as the single-stage solid hydrocarbon liquefaction process according to carboliq make it possible to convert mixed or contaminated plastic waste into high-quality oils that can replace fossil naphtha.

Studies predict that chemical recycling will grow faster than mechanical recycling in the coming decades and will play a key role in achieving the EU's recycling targets. The scalability of the technology and the possibility of long-term offtake agreements with the chemical industry create significant market potential.

7.2.4 Competition and Positioning

The chemical recycling market is characterized by a multitude of technology providers at various stages of development. At the same time, large petrochemical companies, such as BASF, are investing heavily in these technologies to make their raw material base more sustainable. A company with its own sorting and processing infrastructure can differentiate itself through a secure feedstock base and the integration of mechanical and chemical recycling.

7.2.5 Summary

In summary, the market environment for chemical recycling is characterized by strong growth momentum. While mechanical recycling will continue to be relevant, chemical recycling, particularly for complex waste streams, will be the decisive technology for closing the loop. Companies that invest early in this technology and have access to secure waste streams can position themselves as strategically important partners for the chemical industry.

7.3 Corporate strategy

7.3.1 Strategic starting point

KORN Recycling GmbH has established expertise in the mechanical processing of commercial waste. Its existing sorting plant specializes in processing mixed construction waste and bulky waste, enabling the recovery of valuable fractions for material and energy recovery. At the same time, residual streams are generated, which have so far been primarily thermally treated and thus do not contribute to closing the loop. In light of increasing regulatory requirements and societal pressure, the company sees a strategic window of opportunity to reposition itself through the integration of chemical recycling technologies.

7.3.2 Target image and vision

The company's vision is to evolve from a classic waste processor into an integrated raw material supplier for the chemical and plastics industries.

The strategic objective includes utilizing residual streams from the company's own sorting plant, particularly refuse-derived fuel (RDF++), which have previously been insufficiently utilized, and converting them into high-quality secondary raw materials. Specifically, this will be achieved with the help of the The carboliq® process produces an oil substitute that replaces fossil naphtha and can be directly fed into petrochemical processes. This will enable the company to...

It is part of a fully closed circular economy and simultaneously creates new value creation potential.

7.3.3 Competitive advantages and differentiating features

The company can differentiate itself from the competition through several factors. First, it has direct access to mixed and difficult-to-recycle plastic streams from its sorting plant. This reduces its dependence on external feedstock suppliers and minimizes the risk of rising input costs. Second, the combination of mechanical and chemical processes creates synergies, as non-recyclable residues from mechanical processing can be utilized in the chemical plant. Third, the technology enables a measurable contribution to achieving EU recycling targets (recycling quotas) and reducing CO₂ emissions.

7.3.4 Growth Strategy

By entering the chemical recycling sector, KORN Recycling is opening up a new business area that complements the existing mechanical recycling and thus makes the business model broader and more robust.

Thus, the growth strategy serves less to increase throughput in the short term, but rather to strategic diversification, strengthen the competitive position and build new technological expertise in a market that will have outstanding economic importance in the future.

7.3.5 Contribution to company value

Implementing the corporate strategy opens up diverse opportunities for increasing value.

Through vertical integration, the company is evolving from a pure waste disposal company into a producer of high-quality raw materials. This creates new revenue streams through the sale of oil substitutes and potentially tradable CO₂ certificates.

Furthermore, the business model contributes to long-term future viability by proactively addressing regulatory changes and integrating the company into the industry's transformation process.

7.4 Technology and process chain

The technological basis of the planned business model is the patented carboliq process, a method for liquefying solid hydrocarbons. This is a thermochemical process that converts mixed and contaminated plastic streams into high-quality oils.

7.4.1 Feedstock

The plant will be fed with residual fractions from mechanical sorting, in particular refuse-derived fuel (RDF++). These streams are currently only suitable for energy recovery.

7.4.2 The carboliq® process (Direct Liquefaction)

The carboliq® process operates at temperatures below 400 °C and atmospheric pressure. This reduces energy consumption and minimizes the formation of coke and gas. The resulting product, known as Circular Liquid Resource (CLR), can completely replace fossil naphtha.

7.4.3 Process Integration

The process chain includes feedstock pretreatment, the liquefaction process itself, and product storage and distribution. Integration into existing systems

The infrastructure of chemical parks ensures short transport routes and easy integration into petrochemical value chains.

7.4.4 End products and sales markets

The end product CLR is used in the chemical industry as a raw material for steam crackers, in the plastics industry for the production of new plastics, and in other industries as a sustainable raw material alternative. This achieves a true closed-loop system.

7.5 Business Model Canvas

The Business Model Canvas by Osterwalder and Pigneur is an established tool for systematically representing business models and capturing their essential elements in a standardized structure. The nine building blocks of the Business Model Canvas can be described as follows:

1. Customer segments: Customers are primarily the chemical industry (steam cracker operators), plastics producers, and the packaging and consumer goods industry, which must meet regulatory recycling quotas.
2. Value propositions: Production of Circular Liquid Resource (which can substitute fossil naphtha). The process enables the utilization of refuse-derived fuel (RDF++), meets regulatory requirements, and contributes to CO₂ reduction.
3. Channels: Direct marketing to customers, offtake contracts and strategic Partnerships with chemical companies (security of supply).
4. Customer relationships: Long-term, contract-based partnerships, co-development projects with industry partners and strategic joint ventures.
5. Sources of income: Revenue from the sale of CLR, additional income from tradable CO₂ certificates and possible subsidies during the investment phase.
6. Key resources: sorting plant, carboliq reactor plant, secured feedstock Currents, technical know-how
7. Key activities: Collection, sorting and pre-treatment of waste and processing into EBS++, carrying out the liquefaction process, quality control and distribution.
8. Key partners: Technology providers (carboliq), engineering companies, chemical companies, development banks and public institutions as well as municipal waste disposal companies.
9. Cost structure: CAPEX production plant, OPEX for operation, personnel, energy and maintenance, license fees, logistics and administration costs.



Figure 20: Business Model Canvas

The scientific strength of the canvas lies in the fact that it creates a unified language for business models and enables both internal and external stakeholders to quickly grasp opportunities and risks.

7.6 Financial model and profitability

The economic analysis of the business model is based on a detailed cash flow model over a ten-year period. It considers capital expenditures (CAPEX), operating expenses (OPEX), revenues from the sale of oil substitutes, circular liquid resources (CLR), and the financial burden of debt. Based on current assumptions, the picture regarding profitability and investor attractiveness is significantly more restrictive than originally anticipated.

6.1 Basic assumptions

- Plant capacity: 45,000 t/a (not economically viable at smaller sizes) when using KORN EBS++).
- Investment costs (CAPEX): approximately €51.4 million (including infrastructure and engineering).
- Operating costs (OPEX): approx. €20 million/year, consisting of personnel, energy, maintenance, administration and logistics.
- Yield: approx. 66% → Annual production of around 29,500 t CLR.
- Selling price CLR: Model assumption approx. €1,200/t (sensitive to oil and naphtha prices).
- Financing: Mixed structure of equity (29%) and debt (71%). Funding would of course be desirable.

7.6.1 Revenue and cost potential

Based on the aforementioned parameters, revenue at full operation is approximately €32 million per year. This is offset by operating costs of approximately €20 million. This results in annual EBITDA of around €12.5 million, corresponding to an EBITDA margin of approximately 39%.

7.6.2 Operating result (EBITDA/EBIT)

The model calculation shows a positive EBIT from the first full year of operation. Nevertheless, absolute profitability is limited due to the high investment costs. Over the period under consideration, this results in a cumulative EBIT of approximately €70 million, which, given the current capital costs, represents only moderate value creation.

7.6.3 Cash flow projection (10 years)

The free cash flow analysis shows a break-even point from year 7 onwards. Before this point, debt service costs and the repayment of the high initial investments dominate. Only in the second project phase does the plant generate positive cash flows, leading to a cumulative value of approximately €41.5 million by year 10.

7.6.4 Net Present Value (NPV) and Internal Rate of Return (IRR)

The calculations, based on a discount rate of 9.9% (WACC), result in a net present value (NPV) of only €4.4 million. The internal rate of return (IRR) is 11.7%, just slightly above the cost of capital. The buffer against negative market developments is therefore very small, which severely limits its attractiveness to investors.

7.6.5 Sensitivity Analysis

The analysis of the sensitivities reveals the high fragility of the model:

- Capacity utilization: Even at a plant utilization rate of 95%, a positive net present value (NPV) is no longer achievable. The business model therefore requires sustained full utilization – a high operational risk.
- Electricity prices: An increase in electricity costs of just 7.5% results in an NPV of zero. This means that profitability is heavily dependent on energy price developments.
- Selling prices: A 9% decrease in product prices reduces the internal rate of return (IRR) to 0%. The model is therefore highly dependent on stable or rising naphtha prices.

7.6.6 Summary

The financial analysis shows that the project's economic viability is only guaranteed under very specific conditions. The entry threshold of 45,000 t/a results in a high investment risk, while the achievable return of 11.7% is only slightly above the WACC. Furthermore, the sensitivity analysis reveals significant vulnerability to fluctuations in capacity utilization, electricity prices, and product prices.

It follows that the business model in its current form is only of limited appeal to traditional venture capital investors. To increase its attractiveness, substantial optimizations are necessary, particularly through:

- a reduction of the inert content in the feedstock to below 5%
- a significant reduction in energy consumption,
- the optimization of catalyst consumption as well as
- the contractual safeguarding of sales and energy prices.

7.7 Investment Readiness

The attractiveness of a business model for venture capital depends significantly on its scalability, profitability, and resilience to market fluctuations. The updated model assumptions show that while the Carboliq-based project is technologically sound, the current economic environment offers only limited appeal to investors.

For traditional venture capital investors, the return on a single investment – Comparable to a "single garage" – too low in relation to the necessary return expectations. A private equity investor would essentially be more interested in a

technology company involved, which builds a large number of such facilities and scales them via separate operator structures.

At the same time, a first full-scale investment, due to its high risk, should be considered a **first-of-its-kind project** with a typical VC risk curve. However, venture capital firms generally **do not invest the necessary sums** for such an investment case at this early stage .

Accordingly, financing an initial plant is only possible through a **significant assumption of risk by the public sector** . This is also justified by the **public interest** in sustainable economic development and the **resource-efficient recycling of waste**.

7.7.1 Scalability

Unlike many traditional green tech models, this one lacks the option of a low-risk market entry via a smaller, mid-scale plant. Economic viability requires a minimum capacity of 45,000 tons per year, which represents a high entry risk for investors.

Modular scaling is not possible, meaning that the capital requirement is substantial right from market entry. This contradicts the typical investment profile of venture capital, which aims for gradual growth financing.

7.7.2 Technology Risks

The carboliq process, with its TRL 8 technology, is highly developed and extensively tested in pilot plants (Biessey, Vogel, Seitz, & Quicker, 2023). Therefore, the technological risks are low compared to alternative chemical recycling processes. However, the current input qualities of refuse-derived fuel (RDF++) exacerbate the situation: While clear improvements in RDF quality have been achieved in the overall project, an inert material content of approximately 8%, although technically manageable, significantly limits efficiency and profitability. Without improving pretreatment to values below 5%, the technology will not achieve an attractive return on investment in the long term.

7.7.3 Market and Customer Risks

On the demand side, conditions are generally favorable, as the chemical and plastics industries are facing increasing regulatory pressure to switch their raw material use to sustainable alternatives. Additionally, rising CO₂ costs under the EU Emissions Trading System (ETS) are placing an increasing burden on fossil raw materials, while the EU taxonomy and ESG reporting obligations require companies to align their investments with sustainability criteria. Nevertheless, sensitivity analyses show that the business model is extremely dependent on stable sales prices: a decline of just 9% reduces the IRR to zero. Supply contracts with minimum price guarantees are therefore essential to limit the risk.

7.7.4 Return potential

With an IRR of 11.7%, the project is only slightly above the weighted average cost of capital (WACC: 9.9%). For venture capital investors, who typically expect double-digit returns per year and well above 20%, this is not sufficiently attractive. Even under best-case conditions, the potential remains limited, as the high capital intensity and lack of flexibility worsen the risk-return profile.

7.7.5 Financing requirements and investment volume

The capital requirement amounts to approximately €52.4 million for a production plant, of which at least €15 million is needed as equity capital from the perspective of the financing banks.

This high initial capital requirement presents a significant hurdle for venture capital investors. Financing seems more realistic through strategic investors (chemical companies, energy companies) or via public-private partnerships.

7.7.6 Exit Options

Exit paths generally involve strategic buyers, particularly from the chemical and energy sectors, who are seeking access to recycled raw materials. Once the plant demonstrates a stable cash flow over several years, private equity funds may become involved. This is not relevant to our business case.

7.7.7 Summary

In summary, it must be stated that the current business model does not exhibit venture capital readiness in the strict sense under the current conditions. The required plant size of 45,000 t/a, the only moderate return of 11.7%, and the High sensitivity to input quality, capacity utilization, and energy prices makes the project less attractive to traditional venture capital investors. Realistic financing paths therefore lie more in a combination of strategic partners, subsidies, and long-term debt financing than in a traditional venture capital investment.

7.8 Risks and Mitigation

Risk analysis is a crucial component of the business model evaluation. While technological risks are limited due to the high maturity of the process, economic modeling reveals that economic fragility, in particular, poses significant challenges. The following sections outline the key risk categories and potential risk mitigation measures.

7.8.1 Technical Risks

The carboliq process has been extensively tested in pilot plants and, with TRL 8, has reached a high level of technological maturity. However, residual technical risks remain regarding the quality of the feedstock, in this case, EBS++: An inert material content exceeding 5% significantly reduces efficiency and yield. While the current value of approximately 8% is technically manageable, it jeopardizes long-term profitability.

but the

Mitigation: Further improvements to waste pretreatment in the sorting plant are essential to reduce the inert material content to < 5%. In parallel, continuous monitoring of input quality should be established to detect and counteract process disruptions at an early stage.

7.8.2 Economic Risks

Economic risks are the most critical factors for project success. The model shows a high dependence on a few parameters:

- Plant utilization: A positive net present value (NPV) is no longer achievable at 95% utilization. The business model therefore requires sustained full utilization. a significant operational risk.
- Electricity prices: there is a high sensitivity
- Product prices: the selling price for CLR is also very sensitive. This affects profitability. strongly linked to the development of oil and naphtha prices.

Mitigation: Long-term power purchase agreements (PPAs) and hedging strategies can cushion electricity price volatility. On the supply side, minimum price purchase agreements are crucial to secure a stable price level. Additionally, diversifying supply markets can reduce dependence on individual customers.

7.8.3 Regulatory Risks

Regulatory developments are generally a driver for chemical recycling, but they also present uncertainties. There is still no uniform recognition of chemical recycling regarding the eligibility of CO₂ savings in all EU regulations.

Member States.

Mitigation: The company should actively participate in political and industry-specific initiatives to promote the clear recognition of chemical recycling as a CO₂-reducing technology. In the future, CO₂ certificates could also be developed as a source of revenue once regulatory parity is achieved.

7.8.4 Stakeholder Risks

In addition to technical and economic risks, stakeholder expectations also play a role. Critical voices from NGOs could portray the process as "prolonging the use of fossil fuels." Furthermore, there is a potential dependence on a few large customers.

Mitigation: Proactive communication of the environmental benefits (closed-loop recycling, CO₂ reduction) is crucial. Cooperation with municipalities and industry partners increases acceptance. A broader customer base reduces dependence on individual buyers.

7.8.5 Summary

While technological risks are limited by the high maturity of the Carbolig process, the financial models reveal significant economic vulnerability: even minor deviations in capacity utilization, energy, or product prices can render the project unprofitable. Only a combination of input optimization, cost reduction, commercial risk sharing, and regulatory support can stabilize the business model in the medium term and make it more attractive to investors.

7.9 Roadmap and Implementation Plan

Implementing the project requires a carefully phased roadmap that considers technological, regulatory, and economic factors. Unlike many innovative technologies, market entry via a small, scalable production facility is not feasible.

Not economically viable or possible here.

7.9.1 Project Phases

Phase 1 – Preparation (Year 0–1):

Detailed feasibility studies, securing funding, site selection. Simultaneous commencement of negotiations with strategic partners (chemical companies, energy companies) regarding risk sharing. Further optimization of EBS++ as a feedstock.

Phase 2 – Engineering and Financing (Years 1–2):

Development of engineering plans for a 45,000 t/a plant. Definition of the financing structure (equity/debt, public subsidies). Permitting process with a particular focus on emissions regulations (Federal Immission Control Act).

Phase 3 – Construction and commissioning (Years 2–5):

Construction of the plant with extensive investments. Test operation focusing on process stability.

Phase 4 – Commercial operation (from year 5 onwards):

Transition to full operation with 45,000 t/a input. Focus on achieving full capacity utilization (≥ 100%), as even lower values (< 95%) jeopardize profitability. Parallel conclusion of long-term contracts. Phase 5 – Consolidation (Years 6–10):

Optimization of operations, in particular reduction of energy consumption and catalyst use.

7.9.2 Schedule

- Year 0–1: Preparation, funding, location

- Years 1–2: Engineering, financing, permits
- Years 2–5: Construction & Commissioning
- From year 5: Commercial operation
- Years 6–10: Operational optimization, consolidation, potential expansion

7.9.3 Success factors in implementation

- Improvement of the quality of alternative fuel: Reducing the inert content in the RDF++ to < 5% is necessary if no cost-effective disposal routes for the inert residue can be found.
- Risk sharing with partners: participation of chemical or energy companies necessary to mitigate investment risk.
- Energy price management: concluding long-term contracts and hedging to stabilizing electricity costs.
- Regulatory recognition: Clear definition of chemical recycling as CO₂-A mitigating procedure to unlock additional revenue from certificates.
- Project management: Strict cost and schedule control during the construction phase, since delays that jeopardize already tight profitability.

7.9.4 Summary

The roadmap makes it clear that a successful market entry is only possible through consistently structured project management that systematically controls the complex technical, regulatory and economic requirements along the individual phases.

7.10 Financial Model Overview

The following financial model overview shows the detailed development of sales, costs, cash flows and key performance indicators over a period of ten years.

The basis is the assumption of a 45,000 t/a carboliq plant, the profitability of which is assessed based on the free cash flows (FCF), the net present value (NPV) and the internal rate of return (IRR).

Particularly noteworthy are the achievement of break-even from year 7 onwards, the stable EBITDA margin of around 25.0%, and an internal rate of return (IRR) of 12%. The model illustrates that the investment proves financially viable under stable conditions but is also fragile and reacts sensitively to even minor changes.

Jahr	-1	0	1 50%	2 70%	3 100%	4 100%	5 100%	6 100%	7 100%	8 100%	9 100%	10 100%
Umsatz		16.064.660,56 €	22.490.524,78 €	32.129.321,11 €	32.129.321,11 €	32.129.321,11 €	32.129.321,11 €	32.129.321,11 €	32.129.321,11 €	32.129.321,11 €	32.129.321,11 €	32.129.321,11 €
Materialkosten		7.683.134,61 €	10.756.388,45 €	15.366.269,22 €	15.366.269,22 €	15.366.269,22 €	15.366.269,22 €	15.366.269,22 €	15.366.269,22 €	15.366.269,22 €	15.366.269,22 €	15.366.269,22 €
Rohhertrag		8.381.525,95 €	11.734.136,32 €	16.763.051,89 €	16.763.051,89 €	16.763.051,89 €	16.763.051,89 €	16.763.051,89 €	16.763.051,89 €	16.763.051,89 €	16.763.051,89 €	16.763.051,89 €
Personalkosten		793.000,00 €	1.110.200,00 €	1.586.000,00 €	1.586.000,00 €	1.586.000,00 €	1.586.000,00 €	1.586.000,00 €	1.586.000,00 €	1.586.000,00 €	1.586.000,00 €	1.586.000,00 €
Operative Kosten		1.313.718,38 €	1.839.205,73 €	2.627.436,76 €	2.627.436,76 €	2.627.436,76 €	2.627.436,76 €	2.627.436,76 €	2.627.436,76 €	2.627.436,76 €	2.627.436,76 €	2.627.436,76 €
EBITDA		6.274.807,56 €	8.784.730,59 €	12.549.615,13 €	12.549.615,13 €	12.549.615,13 €	12.549.615,13 €	12.549.615,13 €	12.549.615,13 €	12.549.615,13 €	12.549.615,13 €	12.549.615,13 €
AIA		4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €
EBIT		1.721.397,49 €	4.231.320,52 €	7.996.205,05 €	7.996.205,05 €	7.996.205,05 €	7.996.205,05 €	7.996.205,05 €	7.996.205,05 €	7.996.205,05 €	7.996.205,05 €	7.996.205,05 €
Zinsen	-962.992,37 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €	-3.275.984,74 €
Steuern		512.976,45 €	1.260.933,51 €	2.382.869,11 €	2.382.869,11 €	2.382.869,11 €	2.382.869,11 €	2.382.869,11 €	2.382.869,11 €	2.382.869,11 €	2.382.869,11 €	2.382.869,11 €
NOPAT	-962.992,37 €	-1.041.610,80 €	2.216.269,28 €	7.103.089,41 €	7.103.089,41 €	7.103.089,41 €	7.103.089,41 €	7.103.089,41 €	7.103.089,41 €	7.103.089,41 €	7.103.089,41 €	7.103.089,41 €
AIA		4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €	4.553.410,07 €
CAPEX	-25.699.915,25 €	-25.699.915,25 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
Bankkredit Tilgung	-10.699.915,25 €	-25.699.915,25 €		4.549.978,81 €	4.549.978,81 €	4.549.978,81 €	4.549.978,81 €	4.549.978,81 €	4.549.978,81 €	4.549.978,81 €	4.549.978,81 €	
Eigenkapital	15.000.000,00 €											
FCF	-27.625.899,99 €	-21.675.139,52 €	4.754.628,13 €	10.763.383,85 €	10.763.383,85 €	10.763.383,85 €	10.763.383,85 €	10.763.383,85 €	10.763.383,85 €	10.763.383,85 €	10.763.383,85 €	10.763.383,85 €
kum FCF		-49.301.039,52 €	-44.546.411,39 €	-33.783.027,54 €	-23.019.643,69 €	-12.256.259,84 €	-1.492.875,99 €	9.270.507,86 €	20.033.891,71 €	30.797.275,56 €	41.560.659,41 €	
WACC		9,9%										
NPV	4.365.512,31 €											
IRR	11,7%											
Amortisationszeit	7,2 Jahre											
Umsatzrendite		10,72%	18,81%	24,89%	24,89%	24,89%	24,89%	24,89%	24,89%	24,89%	24,89%	24,89%
EBITDA Rendite		39,06%	39,06%	39,06%	39,06%	39,06%	39,06%	39,06%	39,06%	39,06%	39,06%	39,06%

Figure 21: Financial model overview for a 45,000 t/a plant (Source: KORN's own calculations).

8 Summary

In summary, technical evidence was provided demonstrating that a liquefiable and marketable product meeting specifications could be produced using suitable sorting and transport strategies. However, the current economic framework, due to an excessively high proportion of by-products requiring disposal, does not yet permit economically viable operation. This would require either significantly larger plant capacities (>50,000 t/a throughput with correspondingly high investment costs) or improved feedstock qualities (RDF+++). For a plant size of approximately 10,000 t/a of liquid product, a maximum inert material content of approximately 5% is necessary. It was demonstrated that these economic requirements could be met by appropriately re-sorting the waste stream using the technology of Polysecure GmbH or conventional near-infrared sorters. However, this would necessitate retrofitting the existing KORN plant – or would have to be incorporated into future plant planning.

8.1 Sorting attempts

8.1.1 Strand A: Sort4Circle technology

Polysecure GmbH's Sort4Circle technology enables fine-granular sorting of waste streams into over 15 different fractions in a single stage. A series of post-sorting trials on RDF (Recyclable Waste) has shown that the input material still contains a significant proportion of chlorine- and fluorine-containing plastics as well as inert materials, which can be significantly reduced through post-sorting.

Furthermore, considerable variance in the composition of the input stream was observed over time. Sort4Circle can help to level this out by selectively controlling the composition of the output material from the individual sorting fractions.

One of the largest fractions in the sorted material consisted of black materials. These cannot be detected using conventional near-infrared sorting technology. Since their proportion sometimes exceeded 30% and often consisted of potentially recyclable plastics, the project further developed the measurement technology of mid-infrared (MIR) spectroscopy in order to unlock the potential of this material fraction in the future.

8.1.2 Strand B: TBSlight add-on

In a parallel process, the upgrading of the sorting plant at KORN was carried out with a so-called The TBSlight add-on was tested to specifically identify PA/PE multilayer films and reject them as particularly high-quality EBS (recyclable waste). For this purpose, Polysecure's TBSlight technology, which uses fluorescent markers in the material as a sorting criterion, was to be used. However, the investigation showed that the NIR sorter models used in the system could not be modified.

8.1.3 Strand C: Alternative NIR Sort route

- The recovery of single-stream plastics from heterogeneous commercial and bulky waste streams is a key challenge for the expansion of the circular economy. This work involved a detailed investigation of the two-dimensional (2D) material flow of a sorting plant to optimize the separation of PE film, rigid PE, PP, and PMMA while simultaneously minimizing the chlorine content (PVC) and the inert material content.

- The originally planned implementation of tests with labeled plastics could not be carried out due to a lack of adaptation of the NIR systems.
Instead, the available resources were used to conduct a systematic series of tests with real input material. Targeted parameter studies were carried out on both the ballistic separator (varying the angle of inclination and impact frequency) and the TOMRA NIR sorter (varying belt speed, nozzle pressure, and confidence level).
- Additionally, a partial stream was treated with an Arjes shredder with an integrated ferrous separator, which significantly reduced the metal content. In a further step, a mobile non-ferrous separator was used to remove aluminum-coated plastics and other non-ferrous metals. This resulted in improved detectability in the near-infrared range and a significant reduction in the chlorine content in the target streams.
- The results show that a purity-oriented operating mode of the ballistic separator, in combination with finely parameterized NIR sorting and supplementary metal separation, enables the stable recovery of pure plastic fractions from commercial and bulky waste. This work thus provides practical recommendations for optimizing existing plants and highlights the potential of sensor-based sorting technology for securing high-quality feedstock (RDF) for chemical recycling.

8.2 CARBOWEST's annual review

The primary objective of the test—to process KORN's optimized alternative fuels (EBS++) during steady-state operation for at least one week, maintain the process, and produce a marketable petroleum substitute—was successfully achieved. During the first week of operation, an improved operating strategy had to be developed due to various issues and high inert content, which resulted in particularly high diluent oil consumption. Steady-state operation was successfully established in the second week, and diluent oil consumption was significantly reduced. A comparable CLR (Circular Liquid Resource) petroleum substitute was produced compared to high-calorific competitor material.

Due to the lower initial calorific value, only comparatively lower yields of around 50 wt.% could be achieved. However, this is inevitable and logical given the need for mass, material, and energy conservation – the quality of the CLR is comparably high with a slightly lower average calorific value of 44 MJ/kg. With the new operating strategies, longer cycles with lower purge oil consumption will be possible in the future. The generated mass, energy, and material balances are sufficient for initial preliminary design within basic engineering (worst-case scenario). To improve yields, minimizing inert materials in the feedstock through better pre-sorting (e.g., by companies like Polysecure or Steinert) should be implemented. Due to malfunctioning filtration during the balance run (a short-term, irreparable issue prior to the balance run), no solids concentration could be performed in the CLR-Heavy unit, nor could batch-wise solids deconcentration be carried out in the reactor. This resulted in high dilution oil consumption and high selectivity with respect to the CLR-Heavy unit. This, in turn, has three negative effects on the business case:

- *Reduction in CLR product yield (revenue losses)*
- *Increase in disposal volumes (costs)*
- *Reduced plant availability due to purging*

In summary, the key objectives of the operational trip were successfully met:

- *Processing of 18 tons of improved substitute fuel from the company KORN*
- *Successful acceptance (within specification) of the produced quantities to a petrochemical company*
- *Stable and stationary operation after 2 days, lasting a total of 20 days for the Campaign trip*
- *Consistent product quality verifiable through CHNO, GC and SimDist analyses*
- *Low mechanical side currents on non-ferrous metals, ferrous metals, inert materials and Brüdenwasser (good feedstock), only small quantities for disposal*
- *High dust content F3, also due to non-optimized sieve mats*
- *High proportion of residual materials – these should be further processed or minimized*
- *Medium quantities of by-products for disposal*
- *Highly closed balance sheets*
 - *101% mass*
 - *94 % amount of substance; 105% carbon, 119% hydrogen, 83% nitrogen, 68% Oxygen, 27% sulfur*
- *85% enthalpy/energy*

8.3 Economic analysis

The present analysis shows that chemical recycling of EBS++ based on the carboliq process is a technologically viable approach to closing material cycles and can contribute to the industry's sustainability goals. However, in its current form, the model proves to be only partially economically viable.

The high investment requirements for an initial production volume of 45,000 t/a, coupled with the narrow return margin compared to the cost of capital, result in a limited risk-reward profile. To ensure long-term competitiveness, targeted optimizations in raw material quality, energy efficiency, and cost structure are therefore necessary. Strategic partnerships and commercial hedging mechanisms will also be crucial for improving financing.

In conclusion, the chemical recycling of optimized refuse-derived fuels (RDF) is a promising approach, but not yet ready for investors. Its attractiveness depends significantly on whether it is possible to address the economic weaknesses and consistently utilize the regulatory opportunities – particularly in the context of climate targets and CO₂ pricing.

9. Utilization

As requested, the publications and other uses of the project were implemented or prepared. To communicate the project, four LinkedIn posts were written and publicized through a high-reach technology transfer service provider (13,000 contacts, primarily within the Baden-Württemberg innovation community) under the direction of Dr. Marc König.

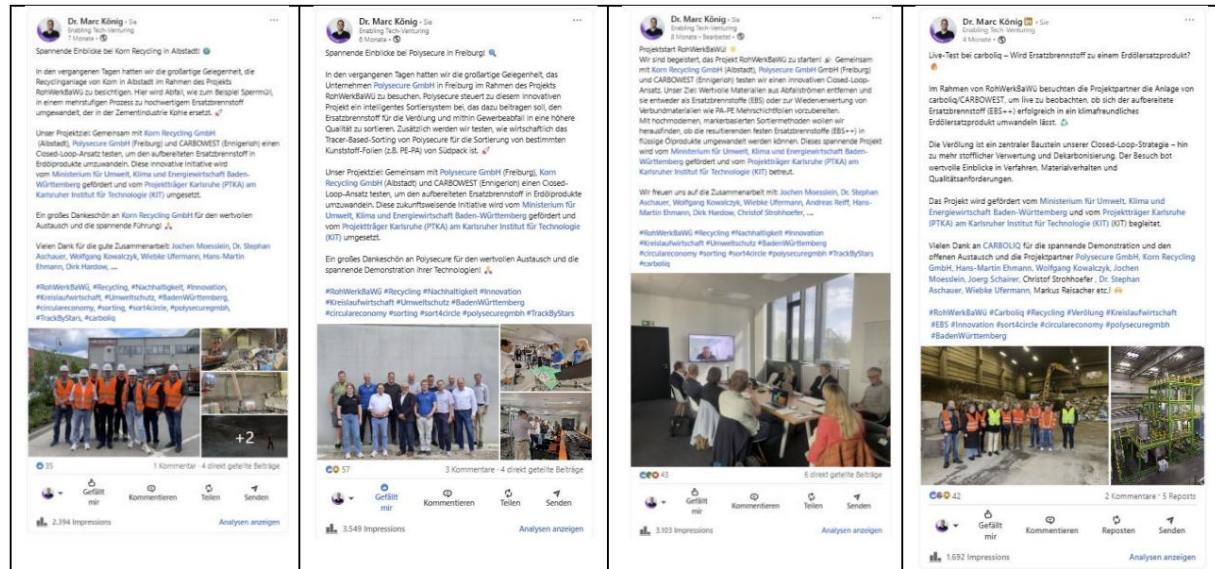


Figure 22: Documentation of project progress and project meetings by Dr. Marc König

As part of the technology transfer concept, a kick-off event with 150 participants and experts from the circular economy took place in Karlsruhe on April 17, 2024.

Furthermore, the project was discussed in a panel of experts and presented to an audience of over 100 participants at the "Green and Energy Innovation" event on December 11, 2024.

Furthermore, an analysis of business models across the entire value chain was initiated in collaboration with a research group, and a corresponding publication was prepared. The value chain to be initiated through the project was examined using a case study approach. The results led to the following publication, which was presented by Dr. Marc König at the ICE/IEEE International Technology Management Conference in Valencia and discussed with an expert audience:

Kling, C., Schützner, F., & König, M. (2025). *Balancing Profit and Purpose in Business Model Innovation: A 6C Analysis of an Emerging Circular Ecosystem*. In *Proceedings of the IEEE 31st International Conference on Engineering, Technology and Innovation (ICE IEEE/ITMC 2025)*, Valencia, Spain, June 16–19, 2025. IEEE.

The paper focuses on the examination of hybrid business models in the circular economy. Using the 6C framework, the conflicting objectives between economic and environmental goals are systematically analyzed. Based on case studies from the fields of waste management, chemical recycling, and sorting technology, the publication demonstrates how companies within an emerging circular ecosystem balance their strategies, shape collaborations, and unlock new value creation potential. In doing so, both challenges and success factors are identified that are relevant for transferring these approaches to other sectors.

Building on this, financing options for the implementation of the technology transfer were discussed at the closing event with relevant stakeholders from the investment sector and comparable innovation projects. Participants included representatives from L-Bank, MBG Baden-Württemberg, INERATEC, various venture capital firms, private investors and business angels, as well as managers from large industrial companies.

A total of 30 people participated in the workshop.

The following members of the project consortium were present:

- Alexander Korn (KORN)
- Jörg Schaier (KORN)
- Hans Martin Ehmann (carboliq)
- Dr.-Ing. Stephan Aschauer (carboliq)
- Gerhard Olbert (carboliq)
- Jochen Mösslein (POLYSECURE)
- Robin Just (POLYSECURE)

Carboliq (represented by Stephan Aschauer) and Polysecure (represented by Jochen Mösslein) each gave a short presentation to outline the specific investment challenges and obstacles to the audience.

The event was moderated by the chairman of Business Angels Stuttgart and a researcher from the University of Leipzig. It was part of the 7th [event name]

Technology Arts Evening with more than 150 participants on July 9, 2025 in Karlsruhe.

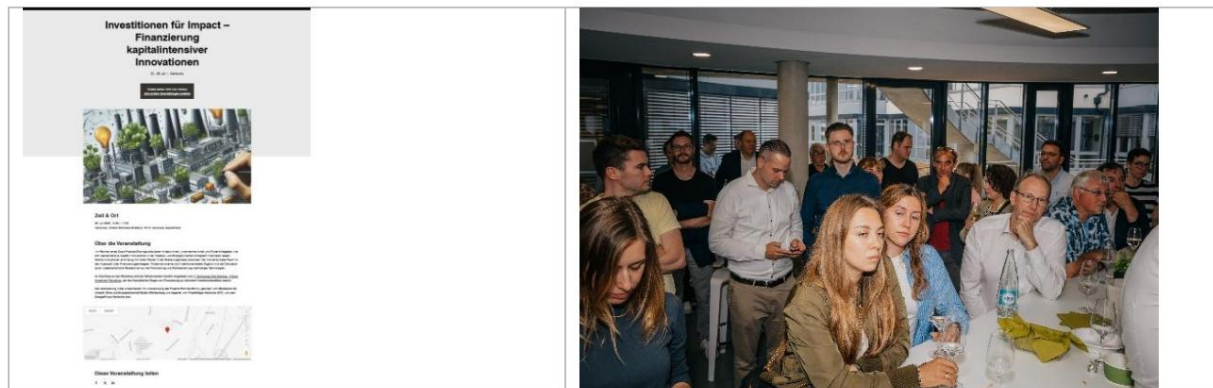


Figure 23: Event information and impressions of the 7th Technology Arts Evening with more than 150 participants in Karlsruhe

As part of the closing event, a poster on **financing capital-intensive impact innovations** was developed. The following poster represents a **first draft version from the workshop**. It brings together key perspectives on impact investments – from general and specific investment requirements and phase-related financing options to obstacles and solutions.

Crucially, financing options must be optimally **coordinated** across the various phases of the development lifecycle. A key aspect of this is the **continuous development and validation of the technology and business model based on verifiable criteria**, which are also tested. Only in this way can it be ensured that investments are targeted and effective, given the long development cycles.

Equally important was the fact that, along the stages from **conception, simulation, laboratory setup, prototype construction to industrial scaling**, the risk was removed step by step from the investment case through systematic checks of the relevant criteria.

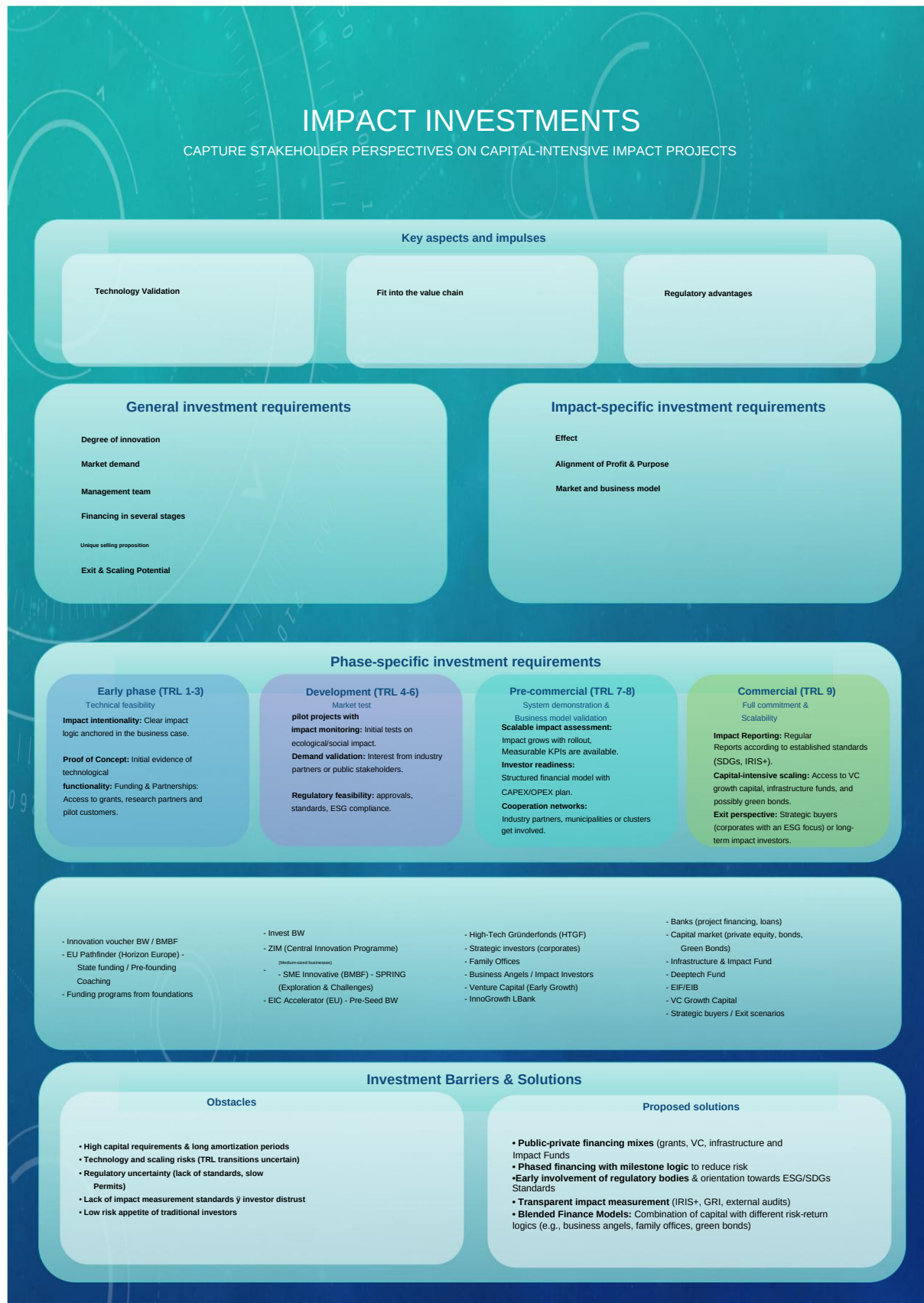


Figure 24: Impact Investments - Capturing Stakeholder Perspectives on Capital-Intensive Impact Projects

outlook

10 Outlook

Following the successful RohWerKBaWü project, further cooperation should be developed based on the results presented here.

KORN's (EBS) feedstock is fundamentally suitable as a feedstock for a large-scale kt/a plant, however, further important investigations and developments are necessary before commercial application.

The advantages of medium-calorie feedstock are:

- High quantities available on the market
- Moderate proportion of contaminants (reduction recommended by re-sorting – e.g., using Polysecure)
- sufficient yields

The next step would involve further feedstock specifications and basic engineering. This should include an assessment of what permanent plant modifications would be necessary and which post-sorting technologies, such as...

Sort4Circle from Polysecure would have to be included in the project design.

Furthermore, a further (longer) test run (at least 1000 hours) is necessary – the so-called 1000-hour test run – using the target material from a commercial plant and the developed operating strategy to further stabilize the process. Should the target material deviate significantly, new operating strategies must be developed before the 1000-hour test.

Procedural guarantees cannot be granted without a successful, trouble-free 1000h test run.

In addition to the disposal of process water, the recycling and disposal of inert residues present challenges. Existing disposal routes to cement plants should be examined and samples sent for this purpose.

Further in-depth analyses regarding the energy consumption of energy input units and necessary plant expansions at the KORN plant in Albstadt could and should be carried out.

In addition to the successful proof-of-concept for the EBS++, other fractions could be used.

This could be done, for example, with the wood fraction G1, which constitutes a significant portion of the material flow at the Albstadt plant and could be effectively extracted and marketed. Furthermore, a CO₂ benefit and crediting are possible for biomass-derived (reclaimed) wood, as biomass exhibits negative CO₂ emissions and is recognized in many areas (e.g., the production of biochar).

Furthermore, the identified quantities of PMMA could also be subjected to mechanical and/or chemical recycling.

outlook

Table 10: Summary of tasks and results

	Work packages	Task	Result
AP1	Analysis of the Initial situation and existing requirements	Analysis of the feedstock flows (characterization of the existing EBS (among other things according to chemical and physical properties, viscosity, density, proportion of inert material, calorific value, chlorine content, ash content)	Potential material flows were identified and observed over 6 months, measured at CARBOWEST and compared – See Table 2 Suitable material flows were selected
		Analysis of technical and economic requirements (evaluation of possible parameters, such as e.g. Throughput, sorting and recycling costs)	See Quality (3.3.1) and Process KPIs (3.3.2) for more information.
		Analysis of organizational requirements (evaluation of legal and organizational framework factors)	
AP2	Development of the Detailed concept of the Sorting and Recycling processes	Comparison of the analysis results from 1.1 (current state) with the requirement profile (target state) according to the CARBOWEST specification	
		Derivation of necessary process specifications and relevant KPIs regarding the further development and application of sorting and recycling technology	Key parameters included - the chlorine content (acceptance risk of the product / (Corrosion of the system) - Inert material content (abrasion of plant components, (Loss of yield, disposal costs) - Contaminants (ferrous and non-ferrous metals) identified
		Development and description of the detailed concept of the sorting and recycling process, taking into account the results from 2.2 Provision of fluorescent tracers and	
AP3	Validation of TBS-light technology for precise sorting of marked items	correspondingly marked PA-PE composite films	A suitable tracer was selected and sufficient stock levels were ensured for the large-scale trial. Test foils with a concentration series were produced for the characterization of the sorting system.

	Composite packaging and validation of the SORT4CIRCLE® Technology as an alternative solution for the specific sorting of commercial waste and other waste streams, generating a new EBS++ product		The production of the marked PA/PE films for the trial was not carried out due to the cancellation of the trial.
		Validation of the TBS-light technology for sorting the marked PA-PE composite films	The experiment was aborted during the preparation phase because the existing NIR sorters proved unusable and no practical alternative could be found.
		Further development of the SORT4CIRCLE® Demo Sorting line regarding the mechanical handling and combined detection of commercial waste	Despite the heavily contaminated material, the detection system functioned reliably. Wood/wood-based materials and paper were added as additional sorting fractions. Extensive data on the commercial waste stream were collected, the algorithm for this stream was verified, and further optimization potential was identified.
AP4 Application of the developed Sorting processes for Generation of EBS++ and PA-PE-Composite film fraction		Adaptation of the sorting process at KORN according to the results from AP2	
		Integration of TBS-light technology within the KORN plant based on the results of 3.1 for sorting the marked PA-PE composite films. Preparation of the marked PA-PE composite films with real feedstock.	Not possible due to technical constraints
		Conducting sorting trials within the KORN plant to produce the EBS++ and PA-PE composite film fraction (2 balance runs).	Not possible due to technical constraints
			only partially possible
		Conducting sorting trials with the SORT4CIRCLE® demo sorting line based on the results of 3.3 as an alternative solution for sorting commercial waste and, if necessary, generating the EBS++ fraction.	Three sorting campaigns with EBS were carried out and evaluated.
		Evaluation of the sorting trials from 4.3 and 4.4 (creation of mass and material flow balances, evaluation of sorting efficiency, analysis of the sorted fractions with regard to purity, inert material content and calorific value, derivation of best possible	For the material compositions found, see diagrams in section 4.1.6. According to laboratory analysis, the sorted material is well suited for liquefaction. Wood and wood-based materials form a large fraction, so that

		Recycling options (primarily material, secondarily raw material)	A separate material recycling process can be examined.
AP 5 Driving the EBS++ KORN faction at CARBOWEST		Pre-characterization of the material in a laboratory reactor	Suitable material, lower processing temperature recommended
		Adjustment of the direct liquefaction plant in Ennigerloh, Westphalia, based on the laboratory data obtained Results (catalyst, product)	Setting based on laboratory results and Experiences
		Preparation for the campaign trip with the Operations team – minimizing Campaign problems,	Briefing at 8 a.m. during the campaign drive
		Campaign drive of at least 14 days to achieve stationary conditions,	A total of 17 days with a few initial difficulties.
		Trip log and accompaniment	Inventories were taken before and after the campaign.
		a. Measurements of the raw materials before and after the campaign run b.	
		Accompanying measurements of the essential product parameters for quality assurance	Measurements on ASG to determine Elemental analyses, total halides, total acid number
		c. Record of the essential plant parameters; Evaluation of the campaign run; a. Mass, energy and	Documented
		material balances	Mass balances were determined and made available to the consortium for evaluation and to the project sponsor for documentation.
		b. Disposal and reprocessing costs of by-products and co-products	Confidential information was identified and documented in the confidential report for the project sponsor.
		Proof of further processing in the refinery / chemical industry - final price of the product,	ISCC+ and shipping documents were provided to the project sponsor – they were not published.
		Report on the campaign trip and initial cost-benefit analyses	Share this report. The full report is available from the project sponsor (non-public) ().
		Numerical basis for a life cycle analysis Economic	Forwarded to scientific partners
AP6 Assessment of the Results, creation		analysis Publications	See Chapter 7, page 56ff.
			<i>Kling, C., Schützner, F., & König, M. (2025). Balancing Profit and Purpose in Business Model Innovation: A 6C</i>

	of publications and Investment planning		<i>Analysis of an Emerging Circular Ecosystem. In Proceedings of the IEEE 31st International Conference on Engineering, Technology and Innovation (ICE IEEE/ITMC 2025), Valencia, Spain, June 16–19, 2025. IEEE.</i>
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Attachment

Bibliography

11 Bibliography

Biessey, P., Vogel, J., Seitz, M., & Quicker, P. (2023). Plastic Waste Utilization via Chemical Recycling: Approaches, Limitations, and the Challenges Ahead. (Wiley-VCH, ed.) *Chemistry Engineering Technology*, 1199 to 1214. doi:10.1002/cite.202300042

Brandt, F. (2004). *Fuels and combustion calculations* - ISBN 3-8027-5801-3. Essen: Vulkan Verlag.

Weppel, J., Ufermann, W., & Aschauer, S. (November 2023). Waste generation, recovery and collection of potential feedstocks for the mechanical and chemical recycling of plastics in Germany. *Müll und Abfall*. doi:https://doi.org/10.37307/j.1863-9763.2023.11.04