PLAST2bCLEANED

The PLAST2bCLEANED process for recycling of WEEE Plastics

22th February, 2024

This Project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N. 821087

PLAST2bCLEANED

Meet the speakers

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TNO

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ICL Group

MARCO GARILLI
Electrolux

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Webinar rules

- This call is being recorded and we will upload it to PLAST2bCLEANED YouTube Channel.
- All participants have been muted.
- For questions in the chat, please introduce yourself with your first and last name, use the chat box for your questions.
- For any technical assistance, please reach out to communication@sustainableinnovations.eu
- Please note that we'll have limited technical assistance during the call.
- We'll be sending out the recording and resources mentioned in the follow up email to everyone who registered.

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Agenda

Time	Topic	Presenter/panel member(s)
9:30-9:40	**Welcome + Intro**	Judith Kessens
9:15-10:30	**P2BC results:**	
9:40 -10:25	• P2BC process	Sebastian Reinhardt / Lucie Prins
Short break of 5 minutes		
10:30 – 10:45	• Advanced sorting	Ainara Pocheville
10:45 – 11:10	• Impact Assessment	Spela Ferjan
11:10-11:25	**Panel discussion**	Tom Caris, Rolands Jaunzems, Marco Garilli
11:25-11:30	**PLAST2bCLEANED video**	Mariana Fernández

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PLAST2bCLEANED

PLAST2bCLEANED introduction

Judith Kessens, TNO

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MOTIVATION FOR PLAST2bCLEANED (Judith)

[1] Forti V., Baldé C.P., Kuehr R., Bel G. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam.

- Global E-waste is one of the fast growing waste streams
- Production, consuming, and disposal of e-waste is unsustainable
- Plastic in E-waste, which can not be recycled due to the presence of legacy additives like bromine flame retardants
- The legacy additives need to be separated in order to be able to subsequent recycle the polymers
- In an environmentally and economically feasible manner

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PLAST2bCLEANED

PLASTics to be **CLEANED** by sorting and separation of plastics and subsequent recycling of polymers, bromine flame retardants and antimony trioxide

- EU project started 1th June 2019, end date: 29th February 2024
- Funded under SOCIETAL CHALLENGES - Climate action, Environment, Resource Efficiency and Raw Materials
- Total funding: € 4 500 830,00
- 10 partners, coordinated by TNO

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Overview of the project

The overall aim of PLAST2bCLEANED is to develop a human and environmentally safe recycling process for Waste Electrical and Electronic Equipment (WEEE) plastics in a technically feasible and economically viable manner.

Key technologies developed within the project are:

- Improved sorting of HIPS and ABS
- Dissolution of Waste Electrical and Electronic Equipment (WEEE) plastics in superheated solvents;
- Separation of additives to concentrate BFR and ATO fractions for recycling;
- Energy efficient recovery of solvent and of polymer.

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Objectives

The overall aim of PLAST2bCLEANED is to develop a human and environmentally safe recycling process for Waste Electrical and Electronic Equipment (WEEE) plastics in a technically feasible and economically viable manner.

1. **Development of a mechanical presorting technology**
2. **Closing 3 loops using dissolution under superheated conditions by separation of:**
   - **(1) the polymer**
   - **(2) the bromine**
   - **(3) the antimony trioxide**
3. **Process integration and scale-up**
4. **Performance testing of process and products**
5. **System optimizing for sustainability and economic viability**

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Consortium

PLAST2bCLEANED

Industry/SME

Recycling Company — Coolrec

Engineering company — JUCHHEIM

Polymer

Bromine fraction

Antimony fraction

Plastics producer — ELIX POLYMERS

Bromine recovery — ICL

Antimony recovery — Campine

End user — Electrolux

Chemical industry

Chemical industry

Research Institutes

Coordinator — TNO

Fraunhofer ICT

Gaiker — Member of Basque Research & Technology Alliance

Dissemination and exploitation — Sustainable INNOVATIONS

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Impact

PLAST2bCLEANED

80%
Desired recovery yield

8%
Increased recycling rate

40% reduction
kton CO2 emissions saved

Closing
3 loops
Recycling of polymers, antimony and bromine flame retardants

Profitability

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Team

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WP-LEADS

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WP1: Advanced sorting

Ainara Pocheville, GAIKER, Spain

WP2: Process development

Annnemieke vd Runstraat, TNO, The Netherlands

WP3: Scale-up

Sebastian Reinhardt, Fraunhofer ICT, Germany

WP4: Performance testing

Ana Rita Neiva, Coolrec, The Netherlands

WP5: Impact Assessment

Toon van Harmelen, TNO, The Netherlands

WP5: Diss., Comm. & Expl.

Mariana Fernandez, Sustainable Innovations, Spain

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PLAST2bCLEANED

The Plast2BCleaned Process

Sebastian Reinhardt (Fraunhofer ICT)
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Lucie Prins (TNO)
lucie.prins@tno.nl

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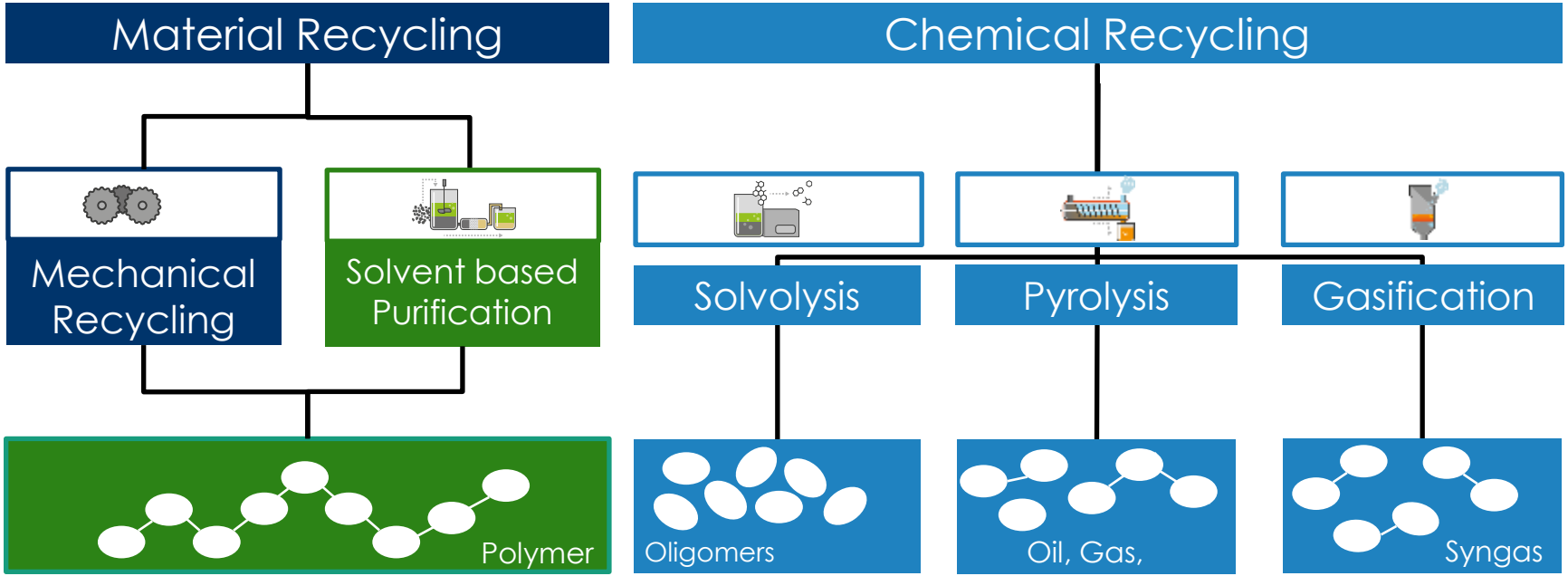
OVERVIEW OF RECYCLING TECHNOLOGIES



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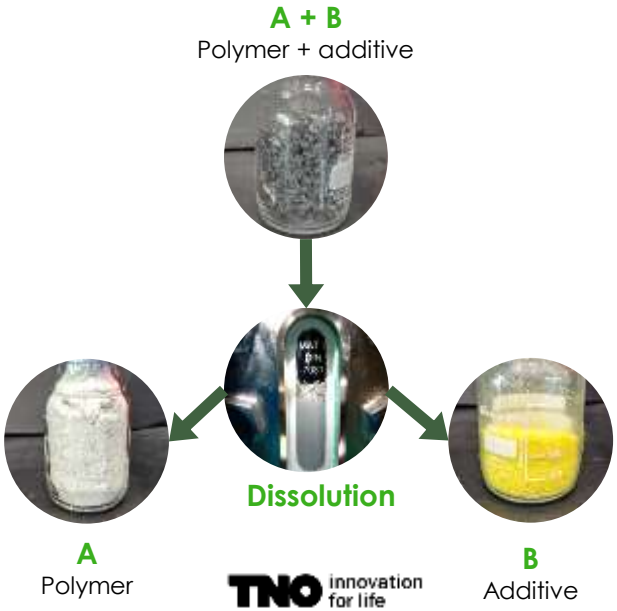
DISSOLUTION



Main characteristics

- Use a single low-boiling solvent above the boiling point
- Pressurised system
- Dissolve the polymer in the plastic
- Thereby release additives
- Remove additives from the polymer
- Recover polymer, additives and recycle solvent

Main benefits

- Energy efficient process
- Potential for high-quality polymers: value retention
- Potential to also recover additives for recycling

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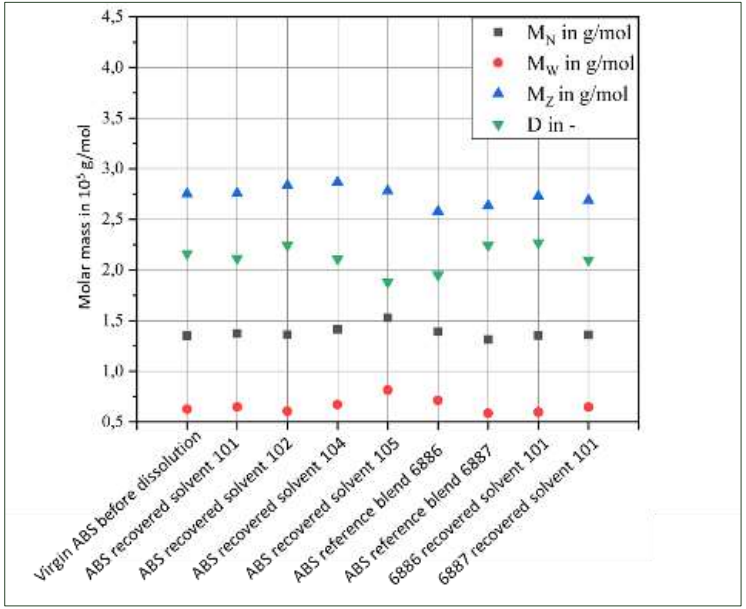
DISSOLUTION

- The polymer is not changed during dissolution, chain length is not affected by the process
- Additives such as Bromine flame retardants dissolve and antimony trioxide is suspended in solution
- Dissolution trials on real waste plastics in kg scale showed an insoluble fraction of ~2%.

Aluminium foil, paper, metals, insoluble plastics from coarse filtration



SEC of ABS samples before and after dissolution

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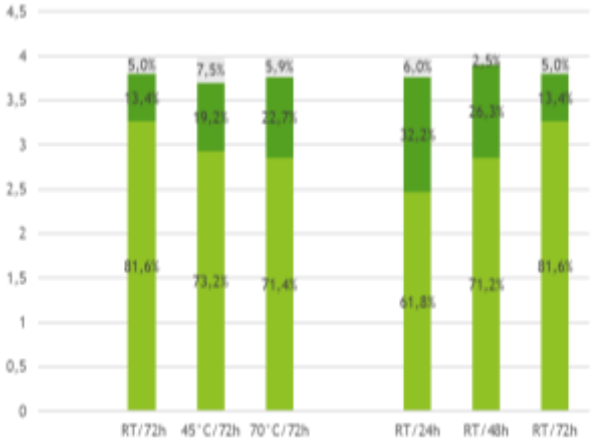
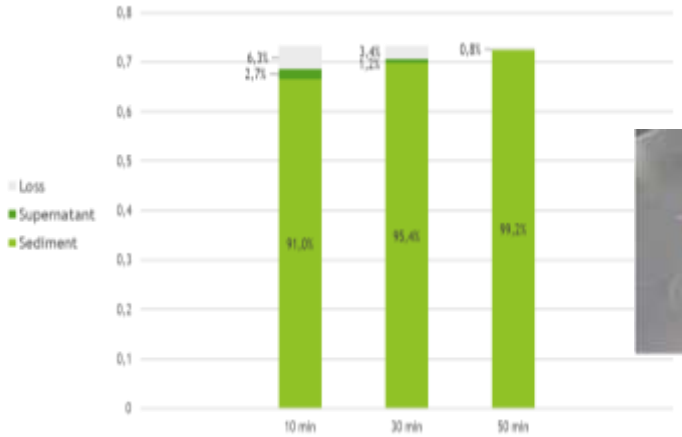
REMOVAL OF ANTIMONY TRIOXIDE

Removal of ATO by density separation

- Density separation tests along multiple approaches (sedimentation, centrifugation, decanter centrifuge) showed good separation on reference substrate (>99% removal)



Sedimentation tests



Centrifugation tests

Recovered ATO fraction
>90% ATO
<0,1% Br

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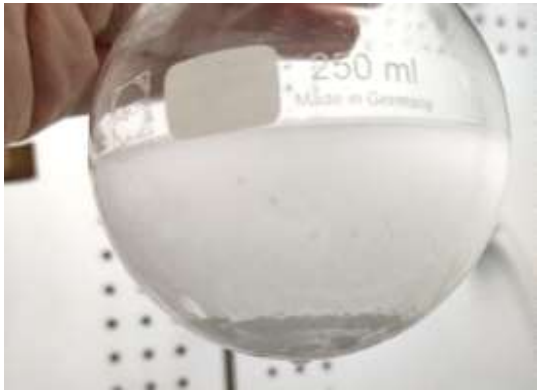
REMOVAL OF ANTIMONY TRIOXIDE

- Antimony trioxide (ATO) will not dissolve → particles are suspended
- Due to high density (5.2 g/cm³) ATO shows sedimentation behavior (but low particle size [0.9 – 1.2µm] makes for slow sedimentation)

Dissolved HiPS

Dissolved HiPS containing ATO



Sedimentation after 72 hours

Supernatant of centrifugation experiment after 10 min, 30min, 50min

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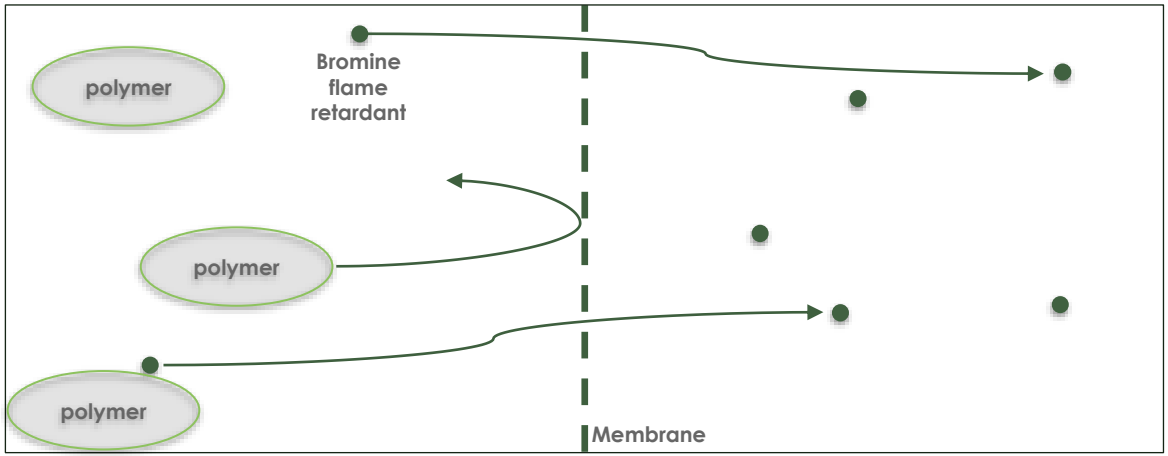
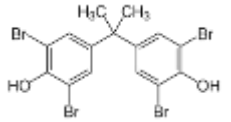
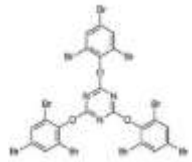
REMOVAL OF BROMINE FLAME RETARDANT

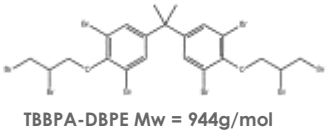
- Dissolved **bromine flame retardants (BFRs)** show molar masses in magnitude of ~**1000 g/mol**.
- Dissolved **ABS** has average weighted mass Mw between **100.000 – 300.000 g/mol**

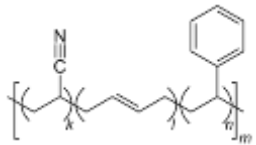


- BFR pass through membrane while larger polymer gets rejected









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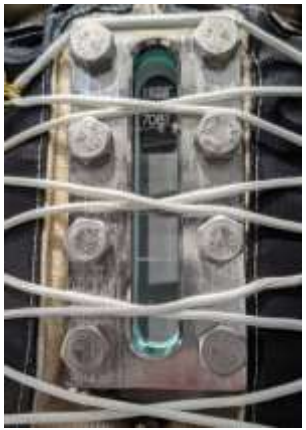
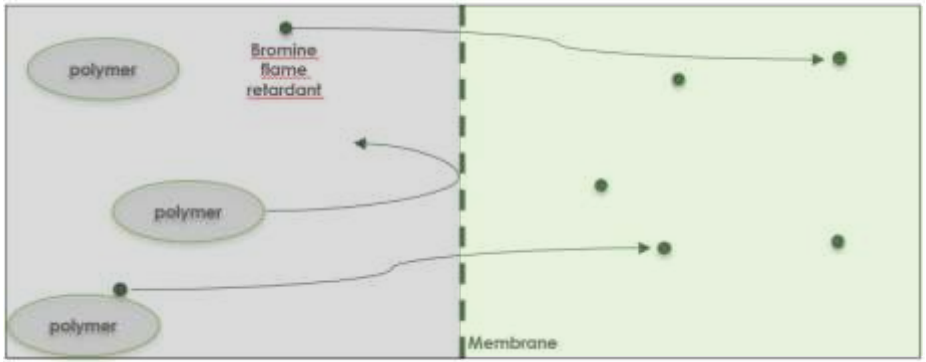
REMOVAL OF BROMINE FLAME RETARDANT

Removal of bromine flame retardant by hot filtration

- The P2BC team developed a hot membrane filtration technology overcoming challenges of high viscosity materials in filtration



Viewing window into grey dissolved mixture of ABS + BFR



Permeate

- solvent

Example of BFR fraction recovered from permeate

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RECOVERY OF ABS AND SOLVENT

Drying of polymer solutions

- When removing solvent from the polymer viscosity increases significantly.
- Then solvent pockets form that enclose remaining solvent in the polymer.
  - Drying with oven, rotary evaporator is impossible.
  - Drying with vacuum extrusion is possible!
- The P2BC team tested spray drying as alternative with success

Tar-like viscosity of polymer-gel

Spray dried rABS

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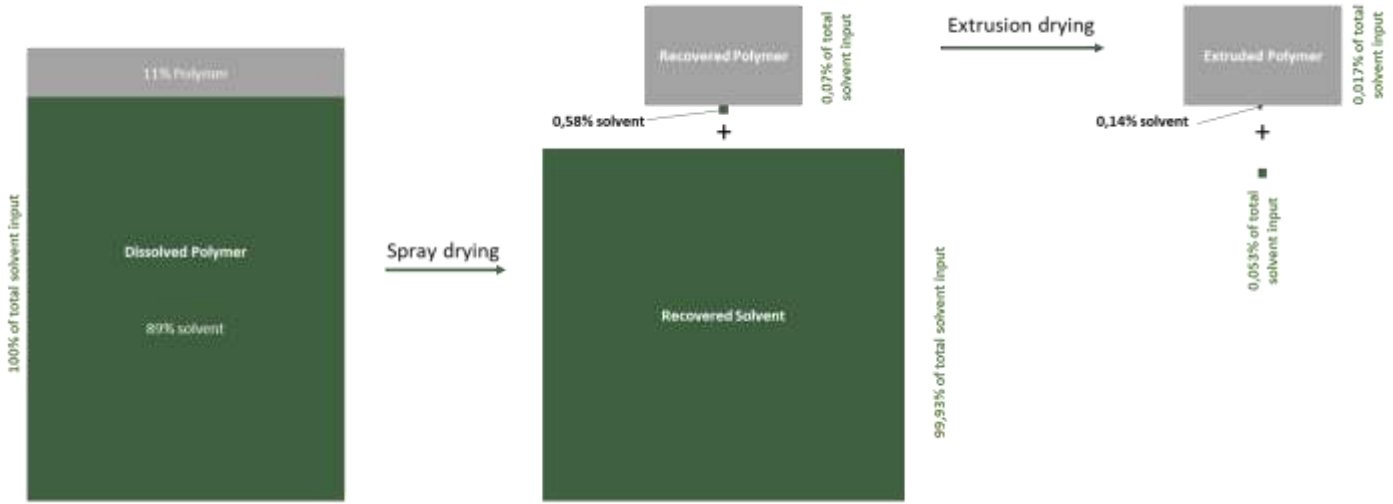
RECOVERY OF ABS AND SOLVENT

Drying of dissolved polymer-mixtures by spray drying

- Spray drying in one step removes >99,93% of solvent
- With added extrusion drying target specifications can be met (<1.000ppm)



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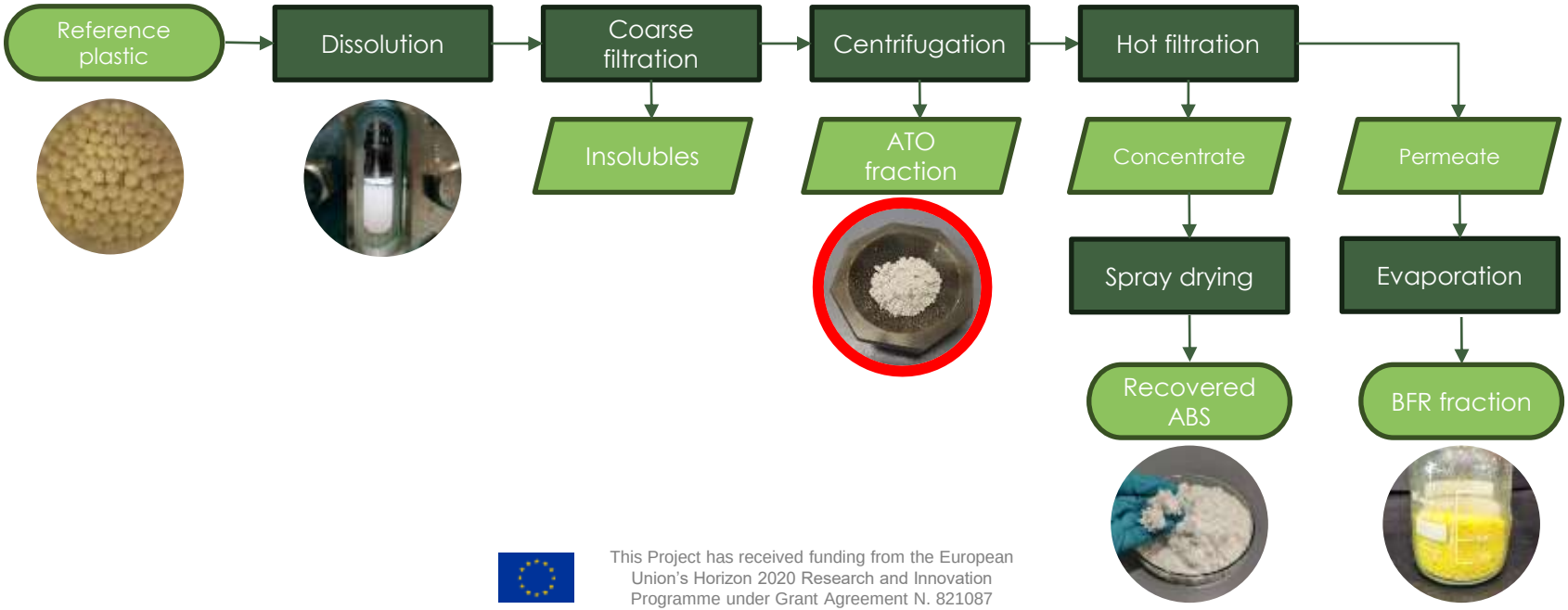
PLAST2bCLEANED PROCESS SUMMARY

Lab scale testing on reference substrate



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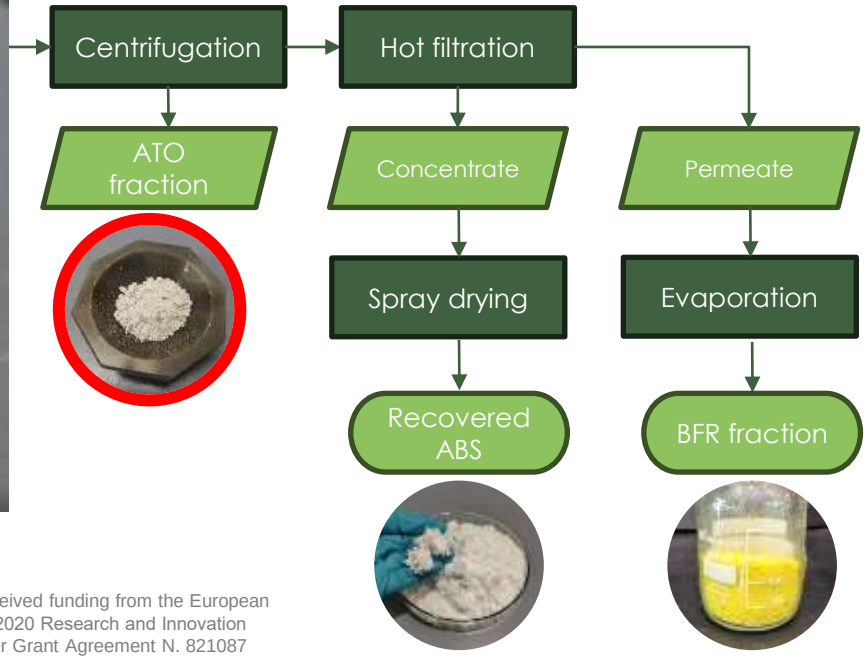

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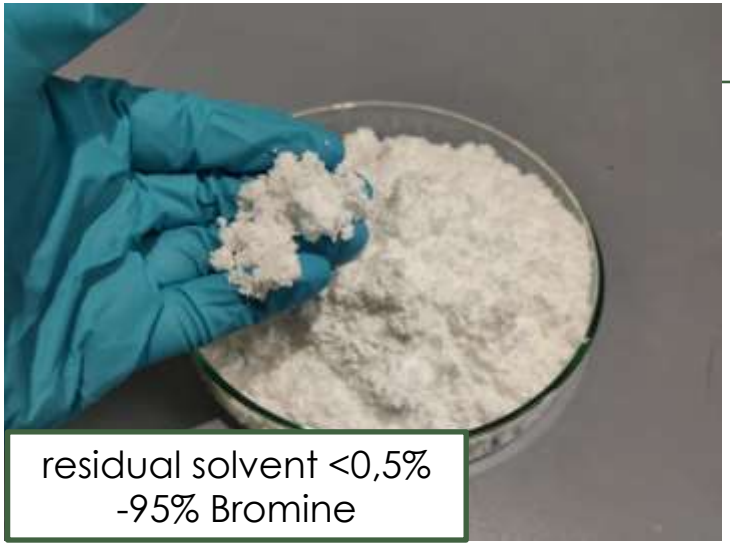

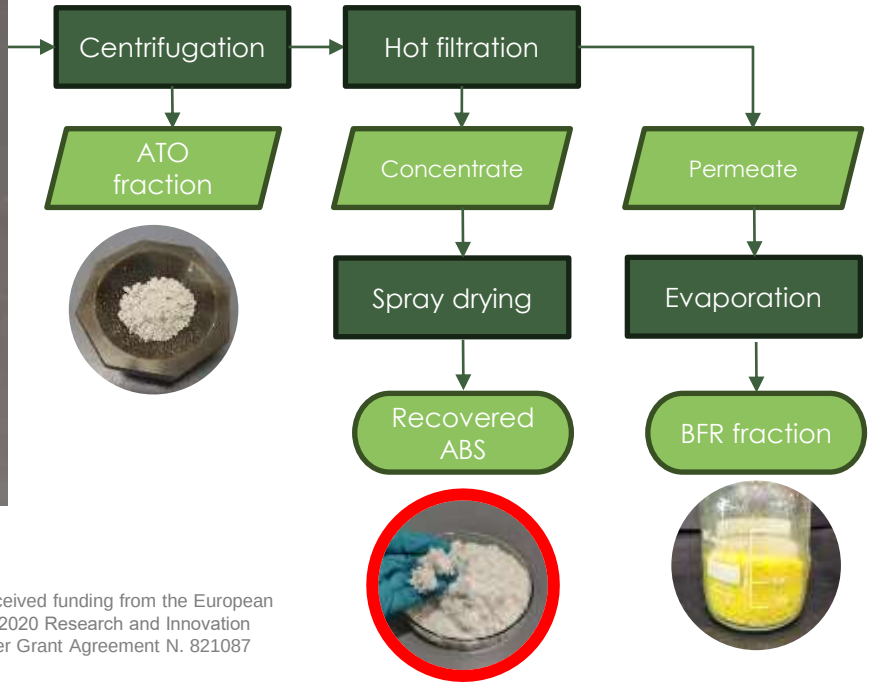

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PLAST2bCLEANED PROCESS SUMMARY

Lab scale testing on reference substrate

Reference plastic → Dissolution → Coarse filtration → Insolubles

469.000 ppm Br
< LoD Antimony

Permeate → Evaporation → BFR fraction

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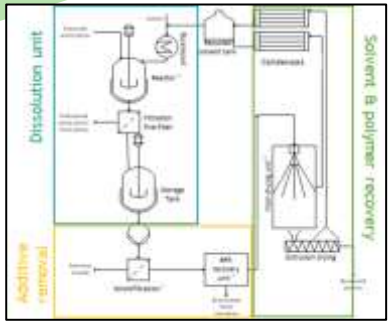
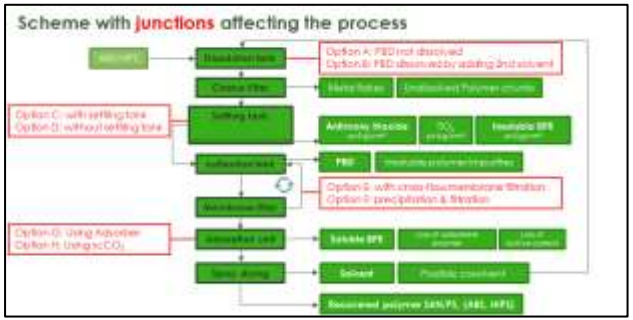
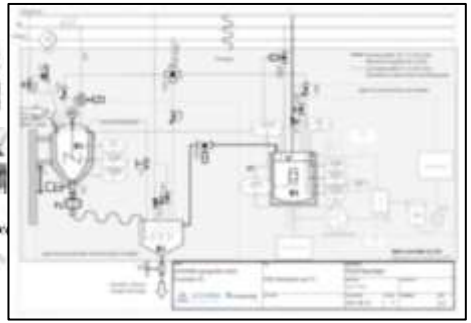
Process development and Scale-up







May 2019

2020

2021

2022

2023

TNO innovation for life

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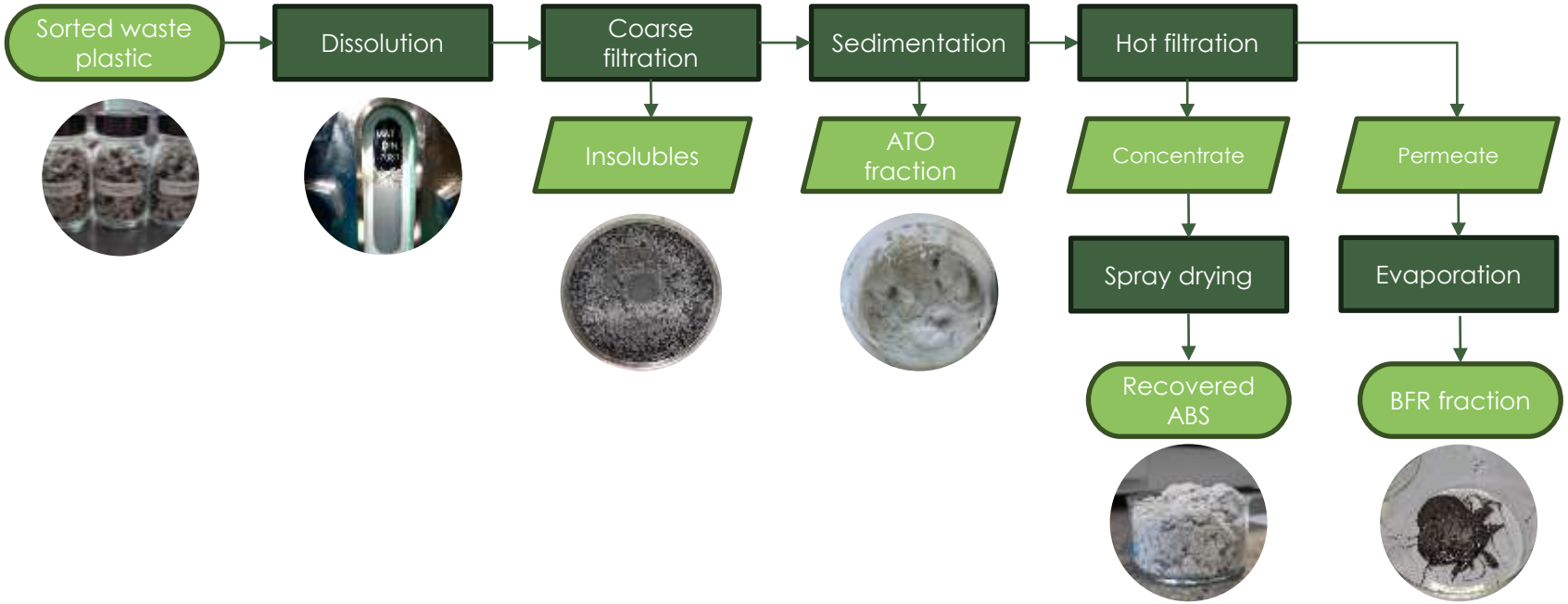
TRL-5 PLANT

Lab scale testing on sorted waste



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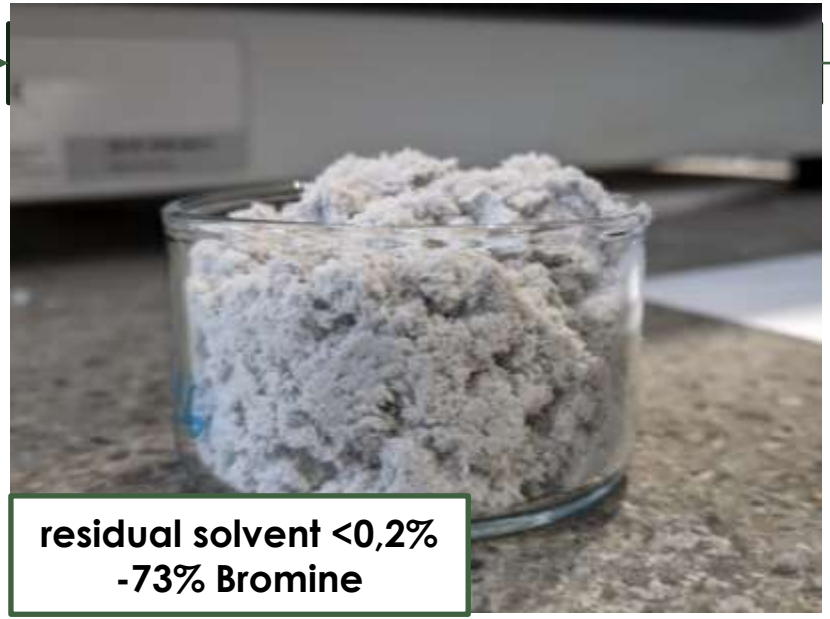
TRL-5 PLANT

Transferring process to sorted waste

Sorted waste plastic



residual solvent <0,2%
-73% Bromine

Hot filtration

Concentrate

Spray drying

Recovered ABS

Permeate

Evaporation

BFR fraction

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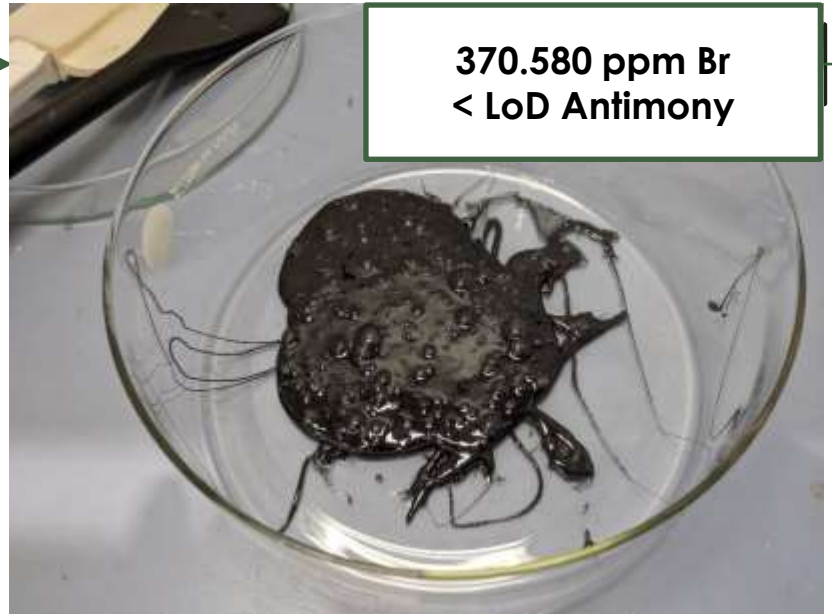
TRL-5 PLANT

Transferring process to sorted waste

Sorted waste plastic



370.580 ppm Br
< LoD Antimony

Hot filtration

Concentrate

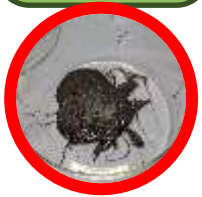
Spray drying

Recovered ABS

Permeate

Evaporation

BFR fraction



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TRL-5 PLANT

Testing at kg scale

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JUCHHEIM Laborgeräte GmbH

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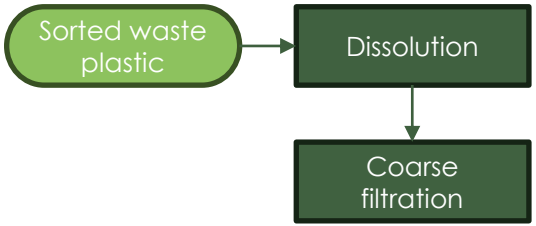
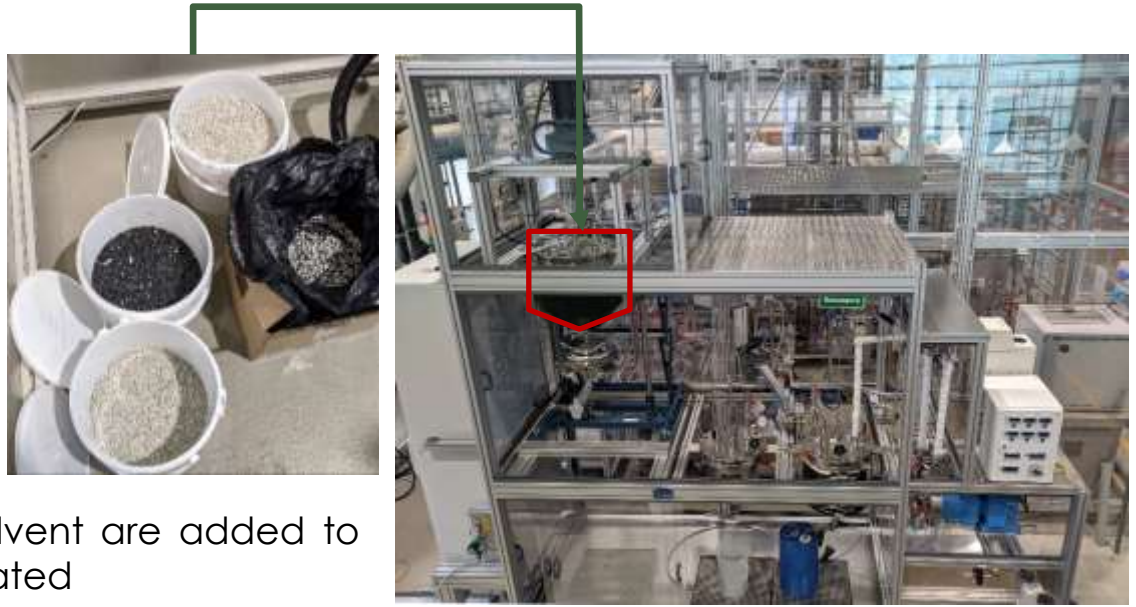
TRL-5 PLANT

Dissolution & coarse filtration





- Sorted waste plastic and solvent are added to the dissolution vessel and heated

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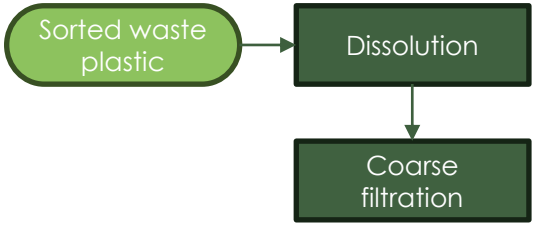
TRL-5 PLANT

Dissolution & coarse filtration



- Sorted waste plastic and solvent are added to the dissolution vessel and heated
- Undissolved material is filtered off

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TRL-5 PLANT

Sedimentation

Coarse filtration → Sedimentation

- Antimony trioxide with higher density settles in sedimentation vessel
- With dip-pipe the upper phase (supernatant) is moved to membrane filtration

Lid of sedimentation tank with adjustable dip-pipe

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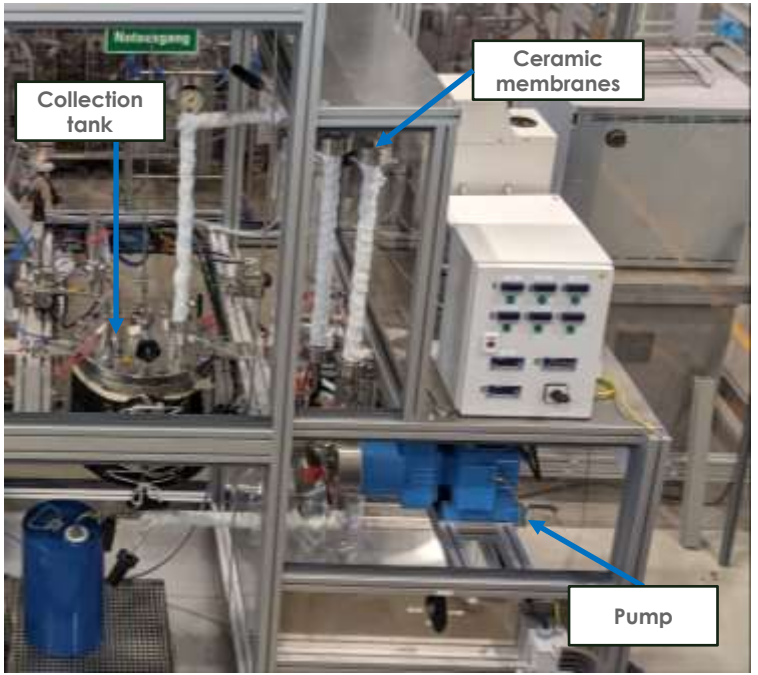
TRL-5 PLANT

Membrane filtration

Sedimentation → Hot filtration

- Mixture of dissolved polymer and bromine flame retardant (BFR) are circulated over membrane
- Small size molecules such as BFR go through the membrane and are removed with the permeate
- Purified polymer remains in concentrate



Membrane filtration unit

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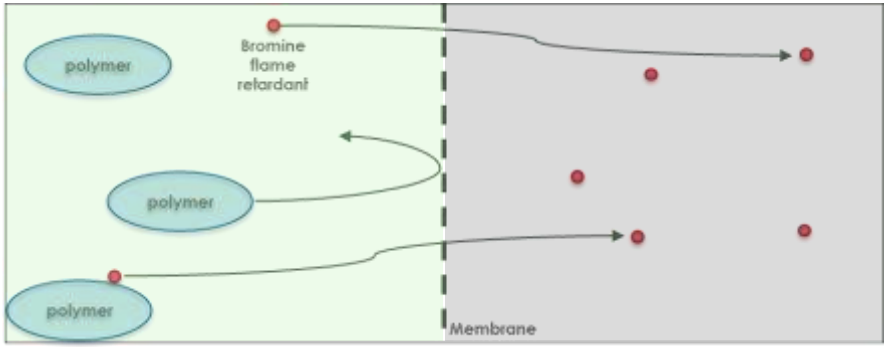
TRL-5 PLANT

Membrane filtration



Spray drying

Concentrate

Permeate flow

Permeate containing high amount of BFR

BFR fraction

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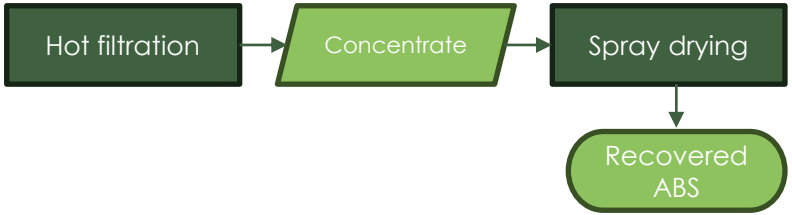
TRL-5 PLANT

Spray Drying



- Purified polymer in solution is dried by spray drying
- Then spray dried rABS can be reused

Spray drying facility

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Open access facility: The TRL-5 facility is open to be operated for anyone interested

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TRL-5 PLANT

Summary

Sorted ABS

Dissolution, sedimentation & membrane filtration

Spray Drying

rABS

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TRL-5 rABS quality

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TRL-5 rABS quality

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TRL-5 rABS quality

rABS passed REACH, SVHC and POP tests

Test Report No. R-2149019

Dated 29-07-2023

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Dated 29-07-2023

Photo:

Result Summary:

Requested tests	Conclusion
REACH Regulation (EC) No 1907/2006 and POPs Regulation (EU) 2019/1021	
SVHC screening test (100 substances)	Pass
Heavy metal content: Lead, Cadmium, Chromium	Pass
Polycyclic Aromatic Hydrocarbons (PAHs)	Pass
Phthalates	Pass
Perfluorinated compounds	Pass
Brominated compounds	Pass
Polychlorinated Biphenyls (PCBs)	Pass
Short Chain Chlorinated Paraffins (SCCP)	Pass

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TRL-5 rABS quality

rABS provided sufficient mechanical characteristics, except for impact strength

		rABS	Elix ABS E401	Elix ABS P2H-AT
Tensile strength (ASTM D638)	Tensile modulus	2550 ± 18 Mpa	1900 MPa	2500 MPa
	Yield stress	37.2 ± 0.08 MPa	37 MPa	41 MPa
	Yield strain	2.0 ± 0.05 (%)	-	-
	Tensile strain at break	18 ± 4.60 (%)	>15%	>15%
Notched Izod impact	(ASTM D-256)	2.02 ± 3.11 kJ/m^2 (Gaiker) 6.4 ± 0.5 J/m (Gaiker)	390 J/m (3.2 mm)	205 J/m (3.2 mm)
	(ISO 180-1A)	5.87 ± 1.84 kJ/m^2 (Elix)	30 kJ/m^2m^2	16 kJ/m^2m^2
MFI (ISO 1133 – 220C, 10 kg)		27.6 cm^3/10min	5 cm^3/10min	37 cm^3/10min10min

→ Recompounding to increase impact strength necessary

Regranulation with 30% rABS & Test bars

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TRL-5 PROCESSING rABS

Reuse of ABS

Spray dried rABS

Densification in a 2-roll mixer

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Moulding trials: prototype production

Prototype production – washing machine door frame

Electrolux

- **Same operating conditions for virgin and recycled ABS**
  - Some burrs with P2bC rABS due to its lower melt viscosity
  - High gloss maintained
  - No visible defects
- **Temperature reduction along the cylinder**
  - Moulding improvement
  - Slight increase of pressure
  - No change in filling pattern
  - Burrs reduction
  - More visible welding lines

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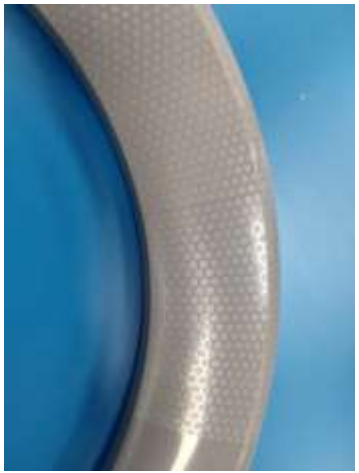
Door frame features



- **Multi-texture aesthetics frame**
  - Excellent finish for all the aesthetics (glossy, matt and textured)
  - No dimensional change vs. virgin-ABS moulded frame
  - No deformation

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Surface paintability

- **Painting test on industrial painting line**
  - Good paint distribution
  - No visible defects
  - Unchanged surface tension
  - High paint adhesion

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Assembly in built-in WM

VIRGIN ABS FRAME

- No problem during assembly
- No frame deformation
- No change in screwing torque during fixing to the rear frame

P2bC rABS FRAME

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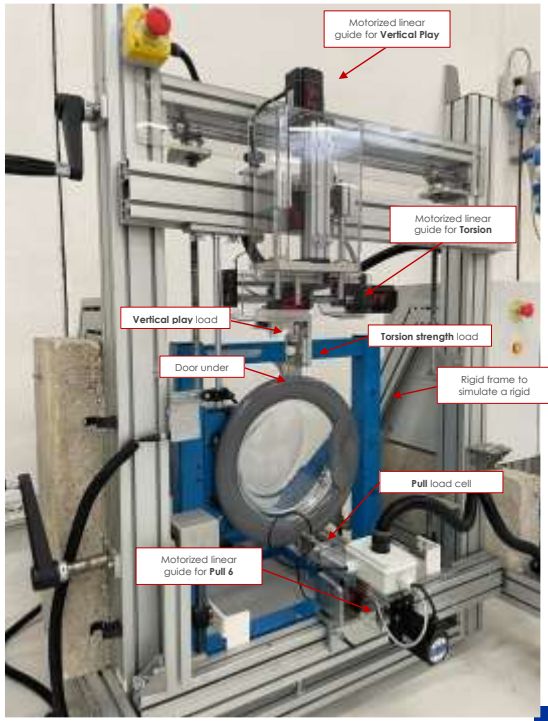
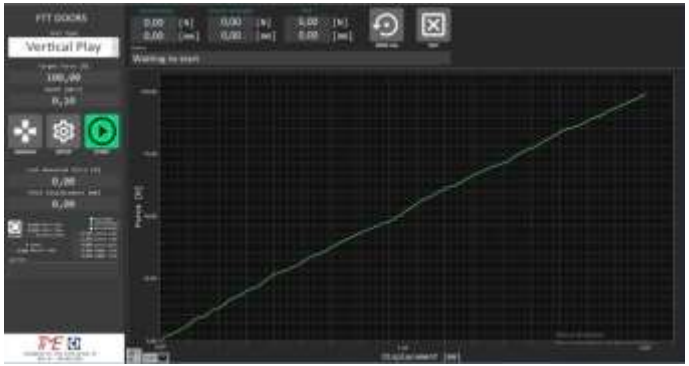
Assembled porthole testing



- Test as in appliance layout
- Three testing modes
- Results as force vs. deformation
- Mechanical performance not effected by use of rABS



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Summary

- The novelty of the Plast2BCleaned process lies in using a low boiling point, single solvent system and adding suitable separation steps for separation & recovery of the additives.
- Antimony trioxide was recovered in high yields (>99%) and adequate purity (>90% ATO, <0,1% Bromine) on reference samples, but not yet on sorted waste samples.
- A hot filtration was established with good permeate flux and no blockage. Filtration tests show a removal of -95% bromine on reference samples and -73% on sorted waste ABS.
- The recovery of polymer provides a dry polymer fraction with solvent residue between 0.1% – 0.5%
- rABS passed REACH, SVHC, and POP tests. Impact strength is improved by recompounding.
- 24 prototype washing machine door frames have been successfully produced, with same operating conditions set for a virgin ABS grade
- Frames moulded with P2bC rABS and virgin ABS are dimensionally identical and P2bC rABS frame does not affect the mechanical performance of the full assembled porthole

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Pre-sorting using RAMAN spectroscopy and machine learning

Ainara Pocheville (GAIKER)
pocheville@gaiker.es

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WEEE plastics recycling

MECHANICAL SEPARATION

Industrial sorting technologies

- Spectroscopy (NIR)
- Density separation
- Electrostatic separation

A LARGE PART OF THESE PLASTICS ARE NOT RECOVERED

TECHNICAL BARRIERS

- **Incorrect identification**
- **High content of additives** (Carbon black, BFR, fillers)
- **Complex mix**: plastics, PCBs, metals, cables…

Challenge to improve WEEE sorting

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Sorting targets

WEEE PLASTICS: Sinking fraction

- Heavy plastics: BFR-rich, black
- **Target polymers: PS~10% , ABS ~ 10%**
- Others: PC/ABS, PC, PP, PMMA, POM, PVC

Coolrec
Part of Renewi

SORTING METHOD

- Technical requirements of recyclers
- Quality requirements of end users

Classification ≥ 80%
Purity ≥ 80%

- Requirements for automation: short measurement time

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Pre-sorting technology

- RAMAN spectroscopy for sensing coloured & dark samples

Raman analysis WEEE plastics
(λ, power, time)

2 Raman spectrometers
Lasers: 785 nm & 1064 nm

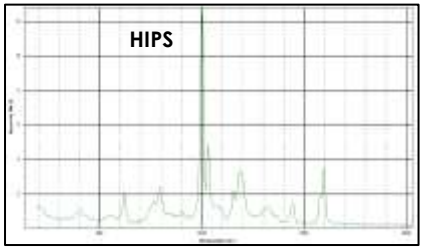
Less Fluorescence

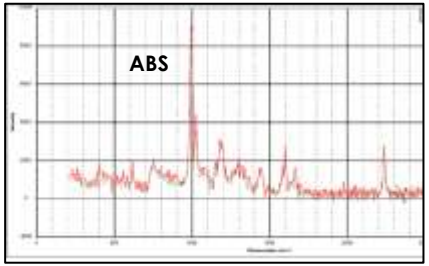
✓ **1064nm**

Chemical identification

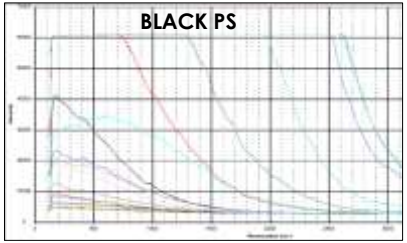
RAMAN spectrum

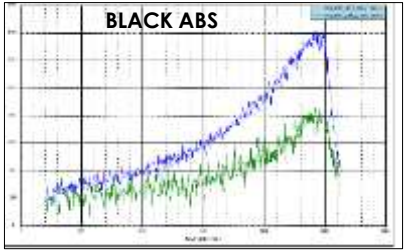
✓ **Reference polymers**
Transparent plastics





FLOURESCENCE
Dark/black WEEE plastics





Difficult to discriminate ABS & PS

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Advanced sorting: RAMAN spectroscopy + machine learning

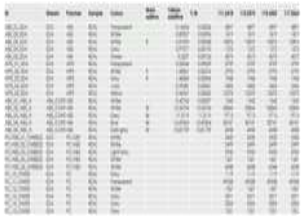
- Classification models for WEEE plastics (TRL 4)

1. Raman spectroscopy

2. Data set construction

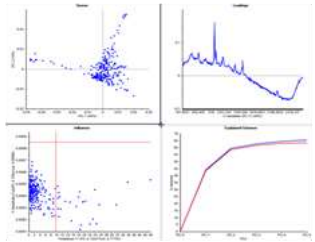
Raman spectral data
Laser 1064nm, t=1s

Representative of the sample (sinking fraction)



3. Pre-processing spectral data

Principal Component Analysis (PCA)



Aspen Unscrambler™

4. Model training (MVA)

- Calibration set
- ✓ Validation set

5. Samples classification

PREDICTION MODEL
CAT 1: HIPS
CAT 2: ABS
CAT 3: PC/ABS
CAT 4: OTHERS

Several models (LDA, SVM)
Different % CLASS-%PURITY

BEST PERFORMING MODEL (LDA)
CLASS. (overall) ~ 60%
Sorted PS & ABS:
CLASS. ~40%,
PURITY ~ 80%

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Achievements

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- **Design, development & testing of a Raman sorting prototype**

✓ Set-up at GAIKER (May 2023)
✓ **Automated Raman measurements & classification of WEEE plastics**

Pilot sorting tests (TRL 5)

TV backcovers & monitors
Test set: 180 samples
(PS, ABS, PC/ABS, PC, OTHERS)

Gaiker
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

LDA MODEL SCALE-UP
- **CLASS: 67% PS & 55% ABS (↑)**
- **PURITY (PS & ABS) ~ 45% (↓)**

TNO

Other machine learning models explored
(ANN, RF, GBM, GLM, Ensemble models)

STACKED ENSEMBLE MODEL
ABS sorting (vs. OTHERS)
- **CLASS. ~ 35%**
- ✓ **PURITY ~ 75%**

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Conclusions & Outlook

Raman spectroscopy with Machine Learning in real-time applications demonstrated

- WEEE plastic sorting using a laser of 1064nm at 1s.

Several classification models to sort PS, ABS and PC/ABS from WEEE streams

- Trade-off: classification/purity rates (80%) were not achieved at the same time
- Black plastics partially identified

Further research on WEEE plastics classification using Raman spectroscopy

- Alternative pilot testing scenarios & spectral data processing.
- New technological solutions: to reduce fluorescence, focal length adaptation.
- Sorting strategies → To increase the purity of sorted polymers.

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Impact Assessment
Spela Ferjan

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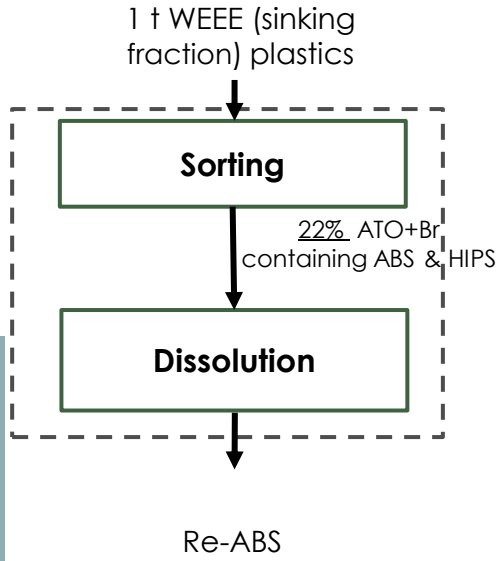
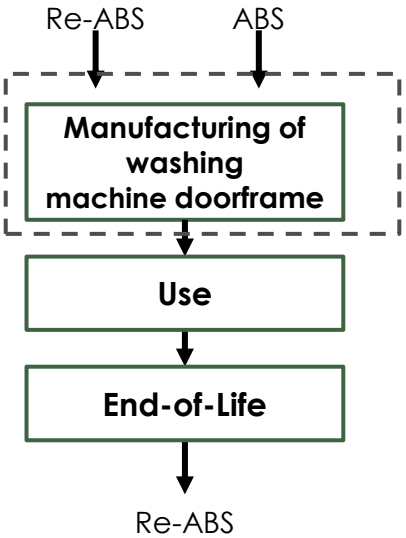
Environmental and economic assessment

WASTE PERSPECTIVE



PRODUCT PERSPECTIVE



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LCA- Carbon footprint

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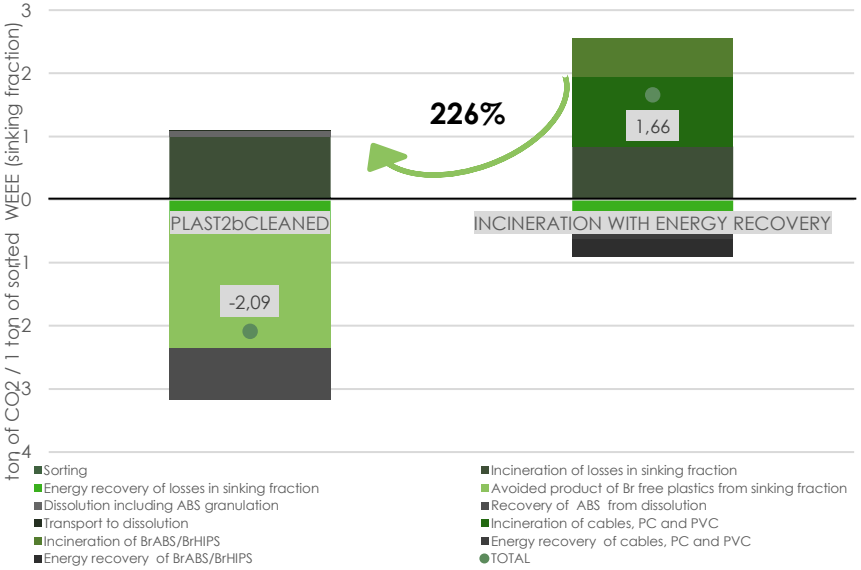
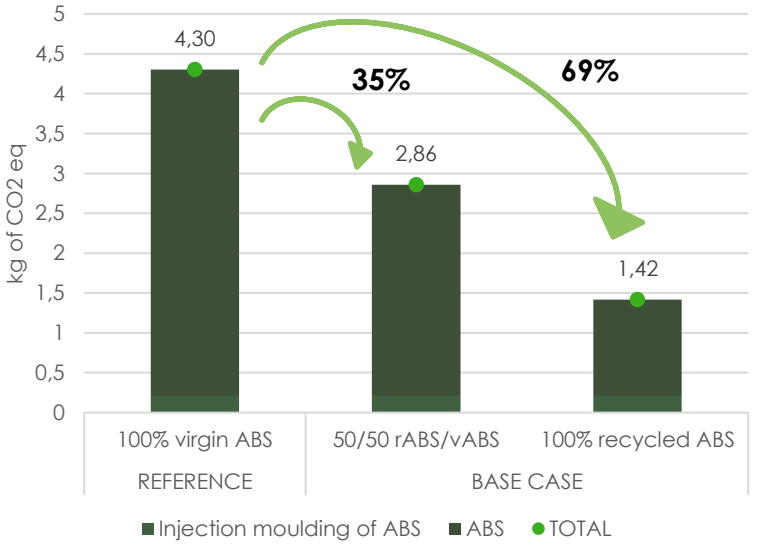
Waste perspective



Reduction potential with SENSITIVITY: **188%**↓

Product perspective



Reduction potential with SENSITIVITY:

- 50/50 vABS/rABS: **24%**
- 100% rABS : **48%**

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LCC – Waste perspective

Final LCC results from a waste perspective		
Costs for pre-processing & sorting (all valuable sinking fractions; 66 %)	234	€/t
Costs for dissolution	1,135	€/t
Costs for EoL treatment of impurities & losses (8 %; 1000€/t)	80	€/t
Total costs per ton	1,449	€/t
Total costs per kilogram	**1.45**	**€/kg**
Recovery of ABS (80% valuable output; estimated market price for vABS: 1,70 €/kg)	**-1.36**	**€/kg**
EoL treatment of soluble Bromine fraction (10 %; 1000€/t)	0.10	€/kg
EoL treatment of Antimony fraction (2 %; 1000€/t)	0.02	€/kg
Total costs per kilogram	**0.21**	**€/kg**
Costs for incineration of BrPolymers according to state of the art	**1.00**	**€/kg**
Net cost savings in comparison to state of the art	*-0.79*	*€/kg*

The LCC scenario analysis shows a positive economic outcome from a waste perspective (avoiding incineration costs)

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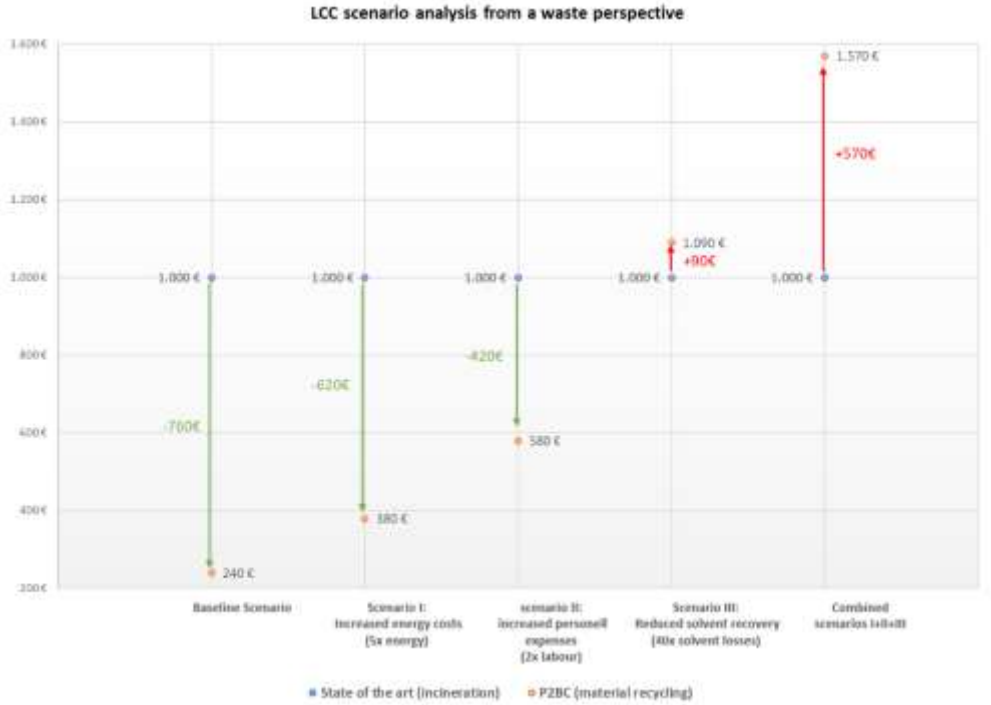
LCC – Waste perspective



The LCC scenario analysis shows large variability / uncertainty

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LCC – Product perspective

Position door frame	Ecofriendly scenario (100% rABS) Costs absolute [€/piece]	Worst-case scenario (100% rABS with energy, labour and chemicals costs increased) Costs absolute [€/piece]
Plastics	1.00 €/piece (↑ +0.15€/piece)	1.76 €/piece (↑ +0.91€/piece)
Labour	0.35 €/piece	0.35 €/piece
R&D, certification and marketing	0.27 €/piece	0.27 €/piece
Overhead	0.23 €/piece	0.23 €/piece
Investment	0.19 €/piece	0.19 €/piece
Maintanance	0.04 €/piece	0.04 €/piece
Energy	0.02 €/piece	0.02 €/piece
Total (incl. OPEX and CAPEX)	2.11 €/piece	2.87 €/piece
Subtotal CAPEX	0.70 €/piece	0.70 €/piece
Subtotal OPEX	1.41 €/piece (↑ +0.15€/piece)	2.17 €/piece (↑ +0.91€/piece)
Reference (100 % vABS)	1.96 €/piece (+ 8%)	1.96 €/piece (+ 46%)

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Impact for Europe

Tom Caris (Coolrec)

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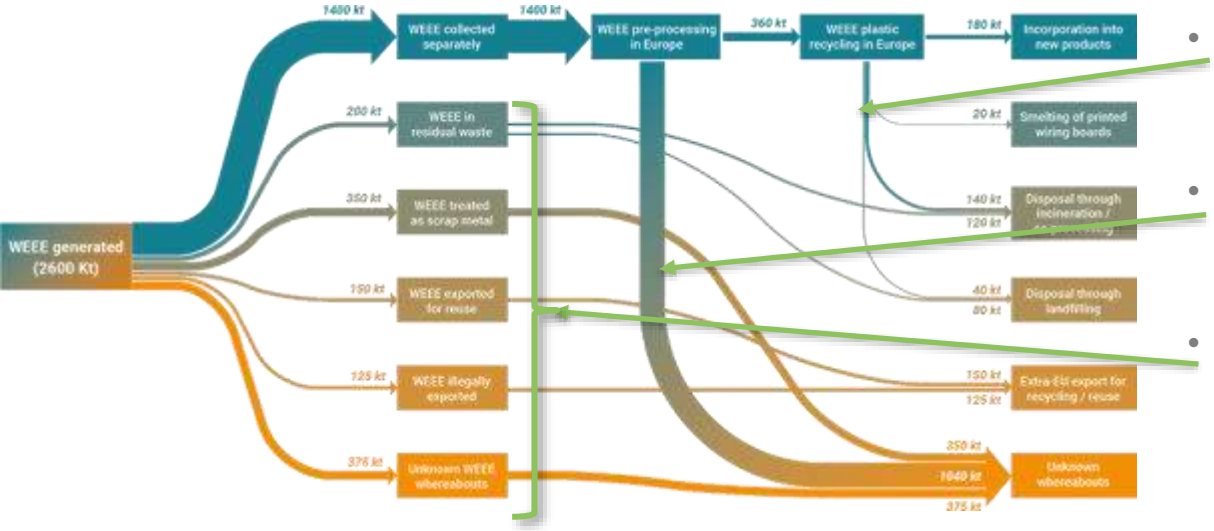
European policies are having huge impact on WEEE plastic recycling

But to recyclers this main stakeholder sometimes feels more like this

Programme under Grant Agreement N. 821087

Potential impact of PLAST2bCLEANED process on WEEE volumes



Estimated fate of WEEE plastics in Europe. Source DSS+
https://www.consultdss.com/content-hub/bfr-impact-weee-plastics-recycling-report/

- 160 kton 'heavy plastics' from EU recyclers
- 1040 kton extra when the plastic waste export ban kicks in
- 660 kton extra when EU collection targets are achieved

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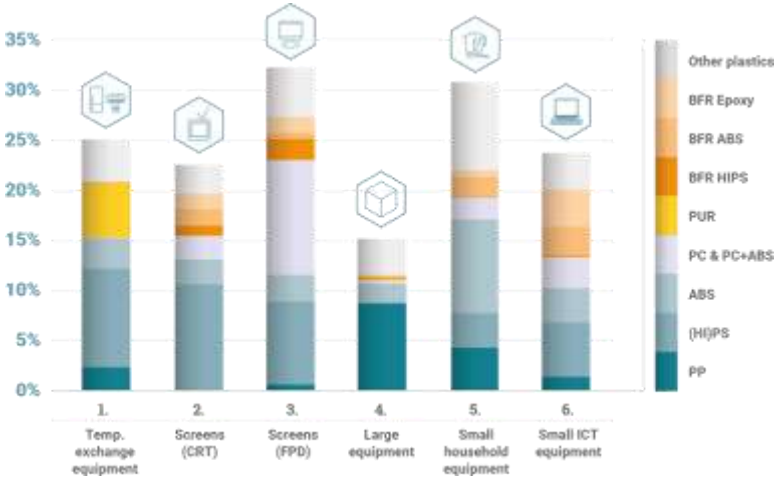
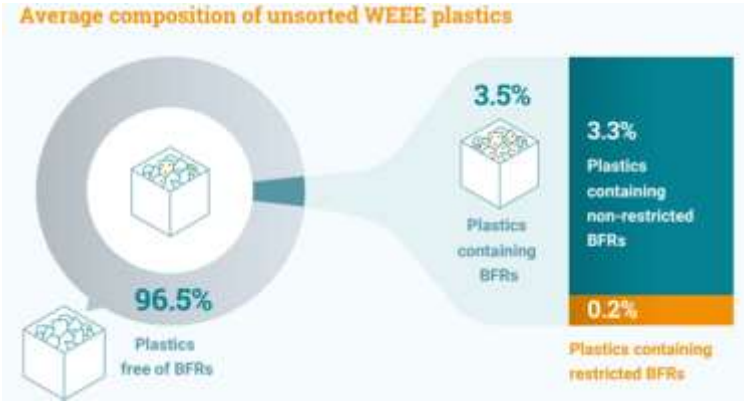
Potential impact of PLAST2bCLEANED process on WEEE volumes



Estimated share of brominated plastics in WEEE plastics. Source DSS+ https://www.consultdss.com/content-hub/bfr-impact-weee-plastics-recycling-report/

If EU collection targets for WEEE are met, there is an estimated potential of **77 kton** that can be recycled extra:

- ABS
- HIPS
- Bromine
- Antimony



Recycling rates can increase by **2.5 to 3%** for screens and small IT equipment

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P2BC panel discussion

Judith Kessens, Tom Caris, Rolands Jaunzems, Marco Garilli

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Panel discussion

Moderator

Judith Kessens,
project manager at TNO, project coordinator PLAST2bCLEANED

Panellists

Tom Caris
Manager business development at Coolrec Group

Rolands Jaunzems
Product stewardship and Sustainability manager at ICL Group

Marco Garilli
Plastic Material Expert at Electrolux Product Technology Labs.

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Video: Project Highlights

Sebastian Reinhardt, a research scientist, and Dr. Ronny Hanich-Spahn from Fraunhofer ICT share insights into the results of the PLAST2bCLEANED project.

They discuss the development of a specialized plant for recycling WEEE plastics, effectively eliminating hazardous components and converting them into harmless substances, contributing significantly to the establishment of a circular economy.

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Click here to watch

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Thank you for your attention

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